PART VI

STUDIES ON CHAIN OF ACCIDENTS (DOMINO EFFECTS)
In all the previous chapters we have dealt essentially with accidents occurring in one industry - or even more specifically one of the units in an industry - at a time. But very often accidents do not take place in isolation and an accident in a unit can be the cause of another accident in another unit which, in turn, may lead to a third accident ... and so on.

In Part VI we present methodologies developed by us to study such domino effects or chain of accidents. Chapter 15 is a reproduction of a paper accepted for publication in Process Safety Progress. Chapter 16 is the manuscript of a paper presently under review with Environmental Modelling and Software.
Chapter 15

MODELS FOR DOMINO EFFECT ANALYSIS IN CHEMICAL PROCESS INDUSTRIES*

In the risk assessment parlance, especially with reference to chemical process industries, the term domino effect is used to denote 'chain of accidents', or situations when a fire/explosion/misfire/toxic load generated by an accident in one unit in an industry causes secondary and higher order accidents in other units. The multi-accident catastrophe which occurred in a refinery at Vishakhapatnam, India, on 14 September 1997, claiming 60 lives and causing damages to property worth over Rs 600 million, is the most recent example of the damage potential of domino effect. But, even as domino effect has been documented since 1947, very little attention has been paid towards modelling this phenomenon. In this paper, we have provided a conceptual framework based on sets of appropriate models to forecast domino effects, and assess their likely magnitudes and adverse impacts, while conducting risk assessment in a chemical process industry. The utilizability of the framework has been illustrated with a case study.

Key words: domino effect, chain of accidents, risk analysis, industrial safety, consequence analysis.

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INTRODUCTION

The biggest industrial accident of the 1990s - the 'HPCL Disaster' (also known as 'The Vishakhapatnam Disaster') which occurred on 14 September 1997 at the HPCL (Hindustan Petroleum Corporation Limited) refinery near the city of Vishakhapatnam, India, has brought into sharp focus the destructive potential of domino effect vis-a-vis industrial accidents. It was this effect (also variously called 'cascading effect' or 'chain of accidents') which was responsible for a single failure in the HPCL refinery with limited damage potential to escalate into a series of major accidents, eventually claiming over 60 lives, causing damage to property worth over Rs 600 million ($20 million), and terrorising a sprawling city of over 2 million inhabitants (Hindu, 1997).

On 14 September 1997 one of the eight Horton spheres, filled with LPG/crude/kerosene and situated near the main gate of the HPCL refinery, caught fire at 6.40 a.m. It then exploded (Figure 1) rocking the entire city and making people think they have experienced an earthquake. The second sphere exploded 15 minutes later and before noon the others also caught fire. The tanks were all full, with crude imports unloaded at the HPCL berth just a few days ago. Fire spread all over the place. People, particularly those living in the vicinity of the refinery, ran for their lives. As the refinery is located in a densely populated industrial belt with several other major industries nearby, a large number of people were directly affected by the happenings at HPCL. Huge tongues of flames and thick black smoke billowed into the sky and joined the hovering monsoon clouds. A sharp shower brought the soot down on the people who saw their white shirts turn black. The rain water flooding the roads was also black and murky.

With both the entrances to the refinery blocked by burning tanks, neither the fire tenders nor the officials could enter the premises for several hours. Only when the contents in the tanks were burnt out could they venture in.

It rained again later in the evening preceded by strong winds when the flames lingered low and closer to the ground. This again created panic among the public but soon more rain poured down to provide some relief.

The death toll which eventually crossed 60 would have been higher had the fire started half-an-hour later than it did, when the first shift staff would have come in to relieve the night shift. And Sunday being a holiday, the administrative personnel, who numbered over 200, were saved as they were not on duty (Hindu, 1997).

The deep scars on the psyche of the Vishakhapatnam residents that this series of accidents have left can be gauged from what happened 9 days after the catastrophe. A loud sound created by some innocent activity near a naphtha tank in the HPCL confines, on 23 September 1997 generated such a panic that workers on duty nearby fled from the scene asking safety personnel of HPCL to raise an alarm which they promptly did. This only helped to spread more panic all over the refinery campus and soon the entire Vishakhapatnam city was gripped with fear. People residing near the refinery complex ran helter-skelter, schools abruptly closed down, shops downed shutters and the entire region was plunged into a war-like situation.

Even as the HPCL's Vishakhapatnam disaster is one of the biggest industrial disaster involving domino effect, it is neither the first instance of its type nor the worst ever. Well-documented instances of chain of accidents in chemical process industries have been
Figure 1. Most probable sequence of events leading to the HPCL's Vishakhapatnam disaster. Thickness of the lines represents the intensity of the heat load impact.
occurring since 1940s; the worst such accident - in terms of death toll - had occurred in Mexico city on 19 November, 1984. The accident, which also involved petrochemicals claimed 650 lives (Pietersen, 1986). Table 1 presents an illustrative list of some of the major domino accidents that have occurred during the last 30 years.

MODELLING OF DOMINO EFFECTS

In-spite of the destructive potential of domino accidents, and the risk which many industries face from their likelihood all over the world, this phenomenon has received much lesser attention than other aspects of risk assessment.

A thorough scan of primary literature based on CD-ROM, INSPECT, and INDEX searches, as also direct search of books and journals, reveals that the available reports on domino effect are by-and-large confined to qualitative description and interpretations of the events that took place during some of the multiple accidents occurring in the past. For example Kletz (1985, 1991), Pietersen (1986, 1990), Mallikarajunan et al. (1988), Pritchard (1989), Bagster and Pitblado (1991), Prugh (1992), and Lees (1996) have described such past multiple accident events and have discussed the various possible ways in which one accident had led to another. The paucity of quantitative studies on this subject can be gauged from the fact that the 3500-page magnum opus by Lees (1996) on risk assessment in process industries contains barely two-page worth of material on domino effect.

A rare quantitative study on domino effect has been reported recently by Latha et al. (1992). They have focused on chain of accidents initiated by fire and have conceptualised various ways in which a fire can initiate domino effect. They have also tried to quantify the heat loads generated by various types of fires, the 'strengths' of the primary accidents thus caused, and the mechanisms by which heat load would disperse and cause vessel failures. But, useful as this work is, it is confined to only a few aspects of fire-related domino effects. Our careful study of past accidents has indicated that there can be several other accident events beside fires which can trigger a chain of accidents. Indeed some of the explosions are so powerful that they can simultaneously cause more than one chain of accidents to begin.

In this paper we have a) catalogued various types of events which can initiate domino effect, b) presented models for analysing and assessing these events, and c) developed a framework for conducting domino effect analysis in chemical process industries. The applicability of the framework has been demonstrated with an illustrative case study.

EVENTS THAT CAN INITIATE DOMINO EFFECT

We have identified the following events which can trigger domino effect:

I. fire,
II. explosions :
   A. blast waves,
   B. missiles,
III. toxic release,
IV. simultaneous and interactive impacts of fire and explosion.
Table 1. List of the important accidents involving domino effect (Lees, 1996)

<table>
<thead>
<tr>
<th>Location</th>
<th>Chemical</th>
<th>Date</th>
<th>Deaths</th>
<th>Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas city, USA</td>
<td>Ammonium nitrate</td>
<td>April, 1947</td>
<td>552</td>
<td>3000</td>
</tr>
<tr>
<td>Nigata, Japan</td>
<td>Natural gas</td>
<td>June, 1964</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Feyzin, France</td>
<td>Propane</td>
<td>January, 1966</td>
<td>18</td>
<td>81</td>
</tr>
<tr>
<td>Texas city, USA</td>
<td>Butadiene</td>
<td>October, 1969</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Crescent city, USA</td>
<td>Liquefied petroleum gas (LPG)</td>
<td>June, 1970</td>
<td>0</td>
<td>66</td>
</tr>
<tr>
<td>Beek, The Netherlands</td>
<td>Pressurized Naptha</td>
<td>November, 1975</td>
<td>14</td>
<td>104</td>
</tr>
<tr>
<td>Westwego, USA</td>
<td>Grain</td>
<td>December, 1977</td>
<td>36</td>
<td>10</td>
</tr>
<tr>
<td>Galveston, USA</td>
<td>Grain</td>
<td>December, 1977</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Texas city, Texas</td>
<td>Liquefied petroleum gas (LPG)</td>
<td>November, 1978</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Borger, USA</td>
<td>Light hydrocarbons</td>
<td>January, 1980</td>
<td>0</td>
<td>41</td>
</tr>
<tr>
<td>Livingston, USA</td>
<td>Petrochemicals</td>
<td>September, 1982</td>
<td>No details</td>
<td></td>
</tr>
<tr>
<td>Mexico city, Mexico</td>
<td>LPG</td>
<td>November, 1984</td>
<td>650</td>
<td>6400</td>
</tr>
<tr>
<td>Antwerp, Belgium</td>
<td>Ethylene oxide</td>
<td>July, 1987</td>
<td>No details</td>
<td></td>
</tr>
<tr>
<td>Antwerp, Belgium</td>
<td>Ethylene oxide</td>
<td>March, 1989</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Pasadena, USA</td>
<td>Isobutane</td>
<td>October, 1989</td>
<td>23</td>
<td>103</td>
</tr>
<tr>
<td>Nagothane, India</td>
<td>Ethane and Propane</td>
<td>November, 1990</td>
<td>31</td>
<td>63</td>
</tr>
<tr>
<td>Bradford, UK</td>
<td>Azodiisobutyronitrile (AZDN)</td>
<td>July, 1992</td>
<td>No details</td>
<td></td>
</tr>
<tr>
<td>Vishakhapatnam, India</td>
<td>LPG</td>
<td>September, 1997</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>
To assess the likelihood of occurrence of these events, and their damage potential, and to forecast whether domino effects would occur and in what sequence, deterministic models have to be used in conjunction with probabilistic analysis. The former type of models are useful in quantifying physical and chemical processes such as size of a leak, chemical release mode and rate, dispersion (including cloud formation), type of explosion and its intensity, heat/missile/shock wave loads generated, etc. The latter type, which are based on careful recapitulation and analysis of past accidents, are needed to work out the probabilities of equipment failure, direction of missiles, direction of fire ball / toxic cloud movement etc.

While choosing the models and conducting analysis based on them one has to be conscious of the following:

a) the computed magnitudes of incident heat and shock-wave effects would have a measure of uncertainty;

b) the stress/strain patterns in vessels effected by fire or fire-explosion combinations would be complex and difficult to quantify with precision;

c) external and transient factors such as wind direction can play a major role;

d) simultaneous occurrence of heat and mass transfer, made complex by transient and rapidly changing nature and magnitudes of the initiating events such as fire due to leakage in a storage vessel, can contribute to the uncertainty.

A typical sequence of a domino accident which indicates the complexities associated with this phenomena, is given in Figure 2.

We now present brief reviews of the events which could initiate domino effects vis a vis accidents in chemical process industries.

Fire as initiating event

Fire is a result of uncontrolled oxidation of chemical in the presence of air liberating heat. Fire in a unit generates heat load, which may be large enough to overcome the creep of the material of construction of the nearby units or build up high pressure in the nearby units due to boiling/heating of the chemicals contained in them. Important aspects of modelling domino effects due to fire include prediction of flame heights, flame merging phenomena in fires in close proximity, the effect of wind on flame tilt and length, and heat load.

Fire is among the most common accident that occurs in chemical industries; it is estimated that fire of large or small magnitude occurs at least once a year. There is considerable possibility that one among ten fires can generate heat load large enough to precipitate a significant accident. Study of past accidents indicates that the affects of major fires are significant upto a distance of 200 m from their point of origin (Kletz, 1983; Roberts, 1983; Kayes, 1986; Davies, 1993; Prugh, 1994) while the spacing between hazardous units is generally kept between 50 to 150 m. It thus becomes very important to model the phenomena of heat load effecting a nearby unit. Several factors would play important roles including atmospheric conditions (which would determine the direction of maximum flux and rate of heat loss), flame geometry, position and orientation of the receiving unit, the nature and state of chemical contained in the receiving (target) unit etc.
Figure 2. Process sequence in a typical domino event
A conceptual model of domino effect triggered by a fire is presented in Figure 3. The following combination of events can be initiated by a fire.

- fire - explosion - release of chemical ...
- fire - release of chemical - fire ...
- fire - flammable chemical release - explosion - ...
- fire - toxic release ...

Which of these combinations would actually occur, would depend upon the source characteristics (release rate, atmospheric conditions, release conditions, etc.) as well as target characteristics (location, operation, chemical in use, etc.).

The severity of fire in terms of heat load is a function of type of release, flammability and the quantity of the chemical involved, strength of ignition source, and finally the type of fire. For example - flash fire and fire ball have higher damage potential compared to pool fire and jet fire for the same chemical and the same quantity. However, the occurrence of particular type of fire event is fully dependent on the release mode, type of operation, operating conditions and mode/strength of ignition source. The anatomy of industrial fire has been discussed by Roberts (1983), CCPS (1989), Pietersen (1990), Prugh (1994), and Lees (1996). Experimental studies (Eisenberg, 1975; Considine, 1984) have suggested that a heat load of 37 kW/m² is sufficient to cause damage in other installations operating under normal (atmospheric) operating conditions. If a unit is operating under extreme conditions of temperature and pressure, the fire makes the unit even more vulnerable to failure.

In general, fire is very likely to produce explosion (vapour cloud explosion and rarefied phase explosion) in units handling liquefied flammable gases under high pressure, cause release of chemical from a unit operating under normal conditions, and cause flash fire/fire ball in a unit dealing with flammable chemicals under pressurised conditions. These scenarios can be further refined by detailed analysis of operating conditions and such information as material of constructions of unit, capacity of unit, orientation of the unit, existing heat load etc.

**Explosion as initiating event**

Next to fire, explosion is the event more capable of initiating domino effect than other type of failures in a chemical process industry.

**The explosion process**

An explosion is a sudden and violent release of energy. In chemical process industries, the energy thus released may be chemical or physical; the destructive potential of an explosion depends on the rate at which the energy is released.

Examples of the violent release of physical energy are the explosion of a vessel due to high gas pressure and the sudden rupture of a vessel due to brittle fracture. Thermal energy is also very important in this context - it often creates the conditions for an explosion rather than being a direct source of energy for the explosion itself. In particular, thermal energy may lead to superheating of a liquid under pressure which in turn would cause flashing off of the liquid if it is let to come down to atmospheric pressure.
Figure 3. Domino effect model for fire as initiating event
Certain types of chemical reactions may release energy large enough to cause explosion. For example, explosion may be caused by a violent release of chemical energy in a vessel due to combustion of flammable gas or decomposition of reaction products in a runaway chemical reaction.

An explosion in a vessel due to chemical reaction tends to be "uniform" while similar reaction in a long pipe gives a "propagating" explosion.

**Deflagration and detonation**

Combustion of flammable gas may lead to two kinds of explosions: deflagration or detonation. In a deflagration, the flammable mixture burns relatively slowly. For hydrocarbon-air mixtures the deflagration velocity is typically of the order of 1 m/s.

In a detonation, the flame front travels as a shock wave followed closely by a combustion wave which releases the energy to sustain the shock wave. The detonation front may reach velocities of the order of the velocity of sound and the hot products of combustion may have supersonic velocities. For hydrocarbon-air mixtures the detonation velocity is typically of the order of 2000-3000 m/s.

Detonation generates greater pressures and is more destructive than a deflagration. But, a deflagration may turn into a detonation, particularly when travelling down a long pipe. Where a transition from deflagration to detonation is occurring, the deflagration velocity naturally exceeds that quoted above.

**Shock / blast waves**

The damaging impact of explosions besides missiles is caused by shock wave, or blast wave. Blast wave generates overpressure which may injure people and damage equipment and buildings. The anatomy of blast waves and their damaging effects have been discussed by Maurer (1977), Baker et al. (1983), Martinsen et al. (1986), Medard (1989), Prugh (1991), Greenbook (1992), Cates and Samuels (1993), Venerate et al. (1993), Van den Berg and Lennoy (1993), and Davies (1993).

An explosion in air is accompanied by a very rapid rise in pressure leading to the formation of a shock wave. Such wave always travels outwards (from the epicentre of the explosion) with the higher pressure parts moving at higher velocities. After it has travelled some distance, the shock wave reaches a constant limiting velocity which is greater than the velocity of sound in the air, or in the unburned gas, as in the case of a vapour cloud. The shock wave has a profile in which the pressure rises sharply to a peak value and then gradually tails off. As the shock wave travels outwards the peak pressure at the shock front falls.

At some distance from the explosion centre, the region of positive pressure, or overpressure, in the shock wave, is followed by a region of negative pressure, or under pressure. The underpressure is quite weak and does not exceed above 4 psi.

The peak overpressure $p^0$, given by the Friedlander equation (Davies, 1993), is related to overpressure at different instants after explosion:

$$ p = p^0(1-t/td) \exp(-\alpha t/td) $$

(1)
Figure 4. Domino effect model for blast wave as initiating event
Where $p$ is overpressure, $p_0$ is the peak overpressure, $t$ is the time, $t_d$ is the duration time and $\alpha$ is the decay parameter.

A study of past accidents (Clancy, 1972; Eisenberg et al. 1975; Pietersen, 1986; Prugh, 1991; Davies; 1993; Khan and Abbasi, 1996b) suggests that an over pressure of 0.7 atm is necessary to cause damage and fatality. In industrial explosions, this order of overpressure is observed over a distance of several hundred meters.

Based on careful studies of past industrial accidents and considering such factors as properties of materials used in the construction of the equipment and the mechanisms of material failure these authors believe that the probabilities of an explosion causing a secondary accident is as much a function of the characteristics of target units, such as material of construction, chemical involved, degree of conjunction, operating conditions, etc., as it is of the overpressure/blast wave (Figure 4). Once we take this into consideration, it would appear that domino effect may occur even when overpressure is less than 0.7 atm if the secondary unit has been weakened in any manner due to corrosion, creep, or fatigue. Recent reports of the continuing post-mortem of the HPCL's Vishakhapatnam disaster (Shankar, 1997), have implicated corrosion as being the prime cause behind the primary accident (vessel failure) leading to domino effect. However, the value of 0.7 atm as the lower limit of damaging overpressure is a useful index because this level of overpressure if reached, would damage an otherwise "fit" unit operating under normal conditions of temperature and pressure.

**Missiles**

When a vessel or a pipe explodes, its walls are shattered into fragments, which are hurled outwards as missiles by the blast.

Missiles are generally classified as primary and secondary. Primary missiles are those resulting from the bursting of a containment so that energy is imparted to the fragments which become missiles. Secondary missiles occur due to the passage of a blast wave which imparts energy to objects in its path, turning them into missiles.

Accounts of the source, types and generation of primary missiles include those of Bowen (1980), Porter (1980), Baker et al. (1983), and Lees (1996).

Primary missiles are generated in three ways: a) bursting of a vessel into a large number of relatively small fragments; b) separation and rocketing of a vessel or a vessel end; c) ejection of a single item.

The number of missiles formed in an explosion involving rupture of a containment varies widely. Large numbers of missiles are produced when a gas filled pressure vessel is shattered. On the other hand a single missile can result if a valve component is ejected due to failure in a high pressure system.

The rupture of a pressure vessel is the most likely mode of vessel failure which can trigger domino effect (Figure 5). The failure may occur even under normal pressure loading due to an existing defect in the container material. But when the container is subjected to excessive gaseous or hydrostatic pressure, caused by combustion or a runaway reaction, the probability of failure is much higher. The probability is further increased if a vessel is subjected to material defect or weakness and overpressure. Vessel failure may involve ductile or brittle fracture. (Bowen, 1980). Ductile failure may not always produce missiles,
but when it does, they have the potential to cause severe damage. Brittle fracture almost always generates large number of missiles.

*Initial velocity of missiles*

Whether a missile generated by an explosion would damage another unit, would depend on whether the momentum of the missile would be high enough to induce failure in the target unit.

The initial velocity of a missile is a function of a) the force or pressure on the missile, b) the transfer of momentum to the missile, and c) the transfer of energy to the missile.

The force acting on a missile depends on the manner of its generation. In case of the rupture of a pressure vessel containing gas, the overpressure may occur due to a slow and gradual rise in pressure or due to a sudden rise as in an explosion. Two types of forces act on the fragments to eject them from the vessel. One is the differential between the gas pressure and the ambient pressure. The other is the dynamic pressure, or wind. In practice, the pressure differential acts only for a very short time, and the acceleration of the fragments is essentially due to the dynamic pressure (Lees, 1996; Khan and Abbasi, 1996b).

In case of rupture of a partition wall by an explosion, too, the forces acting on the fragments are the pressure differential (between the face of the wall and the ambient pressure) and the dynamic pressure. If the pressure incident on the wall is that of a rapidly rising blast wave and the wall configuration is such that the pressure differential across it persists until the wall ruptures, the relevant pressure is the reflected pressure. If, on the other hand, the pressure on the wall rises relatively slowly, the pressure differential is simply that between that pressure and the ambient pressure. In either case, the pressure differential usually acts only for very short time and the acceleration of the fragments is mainly due to the dynamic pressure.

The momentum of the missiles generated from the bursting of a gas filled vessel can also be estimated as the fraction of the available energy which is converted into the kinetic energy of the fragments.

To estimate the force of ejection of an item, such as valve spindle, by a high pressure jet of fluid, an approach based on conservation of momentum may be used.

The impact of a missile in causing domino effect is primarily related to release of chemical (Pasman et al. 1992; Khan and Abbasi, 1996b; 1997) from the target vessel (Figure 5). However, in conjunction with other effects like blast wave or heat load it may load to explosion, or fire as well. An explosion may simultaneously cause blast wave, heat load, and missiles. Hence the probability of domino effect being caused by an explosion can be quite high even though the frequency of occurrence of explosion is lower than that of fire.

**Toxic release as an initiating event**

In 1995 a runaway plume of acrid gases exiting from a rubber processing factory at Pillaiyarkuppam, Pondicherry, India, plunged into a nearby unit engaged in making perfumes. The impact of the acrid plume made the workers in the factory cough and
Figure 5. Domino effect model for missile effect as initiating event
sneeze uncontrollably and when they began to choke, they ran out of the factory premises leaving the giant distillation units unattended.

Fortunately someone had the presence of mind to switch off the power supply before deserting the factory. It took several hours before the air in the factory was cleared and the work could be resumed. Had the power supply not been switched off the reactors would have run unattended and major secondary accidents could have occurred.

In another episode at Pondicherry, in 1996, workers at Shasun Drugs noticed ammonia escaping through a valve of a storage tank. One of the workers rushed to tighten the valve but swooned under the toxic impact of the escaping gas. Another worker who rushed for help also swooned. Luckily this accident occurred when all the safety personnel were in position and the leak was controlled before further damage was done. But it was quite possible that the leak could have occurred at a more unfavourable moment leading to desertion of the factory premises and the consequent operation of the reactors without human checks.

Secondary accidents due to the harm caused by toxic release to supervisory staff have not been a common phenomena in the past. But increasing automation, as a consequence of which lesser number of persons are being deployed for supervising process controllers in an industry, toxic release can harm the supervisory personnel to the extent of making them ineffective thereby forcing a situation in which the processes run without human controls. Major chain of accidents can result in such situations. In developing countries like India, the extent of automation has increased but has not reached the stage common in developed countries where process control rooms are carefully constructed and located so as to minimise danger to them from likely accidents.

To quantify the probability of occurrence of domino effect due to the release of toxic chemicals, the following parameters need to be considered in addition to process details, PIDs, etc. required for all other type of initiating events:

i) control systems employed in the various units in the plant;

ii) detailed description of the human duties and their relative positions in the plant;

The probability of occurrence of domino effect due to this event is likely to be far lower than the other initiating events.

Combination of Initiating events

It has been revealed by various case studies (Kletz, 1985; Marshall, 1987; Raghavan and Swaminathan, 1996; Lees, 1996; Khan and Abbasi, 1995; 1997) that a real-life industrial accident is more often than not a combination of different accidental events (explosion, fire and toxic release) rather than a single event. Therefore, in order to study domino effect, probabilities of occurrence of each type of event should be estimated and the final probability of occurrence of domino effect computed accordingly.

PROCEDURE FOR DOMINO EFFECT ANALYSIS (DEA)

As a first step towards DEA, a detailed consequence assessment should be conducted for the primary event (missiles, heat load, overpressure) at the location of secondary unit using latest models for studying the impact generated at the source of the primary event, directional probabilities (in case of missiles and fire jets), damage radii, scenarios of vessel
failure etc. The sequence of steps to conduct such a domino effect analysis is presented in Figure 6. This procedure recommends use of computer software to conduct detailed consequence analysis. For this purpose, authors (Khan and Abbasi, 1996a) have developed a software package MOSEC (MODEling and Simulation of Explosion in Chemical process industries). This software enables the detailed study of damaging characteristics of industrial fires and explosions. The software MOSEC incorporate four different models of explosion namely confined vapour cloud explosion (CVCE), unconfined vapour cloud explosion (UVCE), boiling liquid expanding vapour cloud explosion (BLEVE), and vented explosion. It also incorporates three models for fires, namely flash fire, pool fire, and fire ball. To estimate the damage potential most of these models use multi-energy method (Van den Berg and Lennoy, 1993).

In subsequent steps of DEA, the probability of occurrence of domino effect is estimated on the basis of the location, contents, orientation, and material characteristics of the likely target units. The analysis employs, inter alia, vessel failure and probit models (Clancey, 1972; Eisenberg et al., 1975; Pietersen, 1986; Greenbook, 1992; Davies, 1993; Lees, 1996; Khan and Abbasi, 1997). If the probability of occurrence of a ‘hit’ is sufficiently high then an accident scenario for the secondary accident is developed followed by an estimation of its damaging potential. This procedure is repeated till the full chain of likely accidents is covered.

To facilitate DEA we propose a two-tier sequence of studies.

**Level I study**

In this section a screening is done in order to identify the units which may come under the spell of domino effect. For this purpose threshold values of different damaging effects reported in references Eisenberg et al. (1975), Clancey (1972), Pietersen (1986), Pasman et al. (1992), Lees (1996), and Khan and Abbasi (1997) are used. For example, it is reported that an overpressure of 0.7 atm can destroy a unit by blast wave impact, a heat load of 37 kW/m\(^2\) is sufficient to induce vessel failure, and a missile (sharp edged) having a velocity higher than 75 m/s has sufficient potential to penetrate the target unit provided that it collides with the unit. If the estimated values of these parameters at the location of the target unit are higher than the threshold values, a detailed analysis or level II study is then performed.

**LEVEL II study**

At level II, more detailed analysis has to be conducted to verify the existence of domino effect, using the damage potential of the primary event and the characteristics of the secondary unit. The characteristics to be considered are:

- material of construction of the unit,
- process chemicals with operating conditions,
- quantities of chemicals in use,
- properties of the chemicals,
- location of the unit in terms of distance and degree of conjunction, and
- prevailing wind direction.
Figure 6. Procedure for domino effect analysis
Using these characteristics and damage potential of primary event, the verification and probability estimation for a secondary event (domino effect) can be worked out as follows.

**Heat load**

Some 60% of the total heat radiation incident over a vessel would be absorbed by the vessel shell and the remaining 40% would be absorbed by the chemicals in the vessel to raise the temperature/pressure of the contents (Latha et al., 1992)

i) Vessel failure due to high pressure build-up

The probability of secondary accident due to heat absorbed by the chemical:

\[
0.40q \times A_r = M \times C_p \times DT
\]

where, \(C_p\) represents specific heat of chemical \((kJ/m^2/°C)\), \(DT\) is temperature difference, \(M\) is mass of chemical \((kg)\), and \(A_r\) is area of vessel \((m^2)\).

The rise in temperature can be translated in terms of pressure rise by using ideal gas law; assuming the content (in case of pressurised gas) as near to ideal gas. For liquefied gases the energy absorbed by the chemical would lead to the formation of vapour.

At temperature \(T_2\), the fraction of vapour generated is governed by (Kayes, 1986; Greenbook, 1992).

\[
f = 1 - \exp(-C_p(T_2 - T_1)/H_v)
\]

and

\[
V_{vap} = f \times V
\]

where, \(H_v\) is heat of evaporation \((kJ/kg)\), \(V\) is total volume of chemical \((m^3)\), \(f\) is fraction of vapour and \(V_{vap}\) is volume of vapour generated \((m^3)\).

The pressure developed in the vessel:

\[
P_2 = n \times R \times T_2 / V_{vap} + P_1
\]

If \(P_2\) is greater than the relief pressure, it may lead to release of the chemical contained in the vessel and if it is greater than the design pressure then the vessel may burst. The degree of excess pressure and the mechanical properties of the material of construction of the vessel would bear upon the severity of the secondary accident. The probability of an accident due to rise in pressure is given by:

\[
\text{Prob}_{\text{heat2}} = (P_2 - P_{\text{relief}}) / P_{\text{relief}}
\]

ii) Vessel rupture due to material failure

The probability of vessel failure due to loss in the strength of the material of construction of the vessel can be computed using maximum strain theory (Bhattacharya, 1986). Heat load developed due to fire would raise the temperature of the vessel wall (radiation is the dominant mode of the heat transfer). This rise in the temperature will reduce the maximum allowable stress of the vessel. This phenomenon is quantified by using the following equations:

\[
T_2 = \left(\frac{(\varepsilon \sigma^* T_{\text{fire}} - q)}{(\varepsilon \sigma^*)}\right)^{1/4}
\]
In order to quantify the impact of temperature on the maximum allowable stress, these authors have developed an empirical equation taking into consideration a total of 15 common materials of construction over a wide range (50 to 1200°C) of temperature.

$$E_{\text{ymax}} = \text{function (temperature)}$$

$$= 1 \times 10^8 (1.858 - 0.0062^* T_2 + 1.691E-05 \times T_2^2 - 1.959E-08 \times T_2^3)$$

Where, $E_{\text{ymax}}$ is maximum allowable stress in N/m² (property of the material of construction), and $T$ is temperature in °C. The stress developed in the vessel due to rise in the internal pressure of the vessel is quantified using following equation (Bhattacharya, 1986)

$$E_Y = P_2 [(1-\gamma) + 2K (1+\gamma)]/(K^2-1)$$

Where, $\gamma$ denotes Poisson ratio, $K$ denotes diameter ratio, $P_2$ is Pressure in the vessel in N/m².

Subsequently the probability of vessel failure due to failure of the material of construction is estimated as:

$$P_{\text{fail1}} = E_{\text{ymax}} / E_Y$$

Finally the probability of secondary accident due to heat load is computed using the function:

$$P_{\text{heat}} = P_{\text{fail1}} \cup P_{\text{heat2}}$$

$$P_{\text{heat}} = \text{minimum}[1, \{1-(1-P_{\text{fail1}})*(1-P_{\text{heat2}})\}]$$

*Blast load (overpressure)*

When a blast wave developed due to an explosion hits an object, it causes a diffraction/drag type of impact. The likely damage due to such impact is measured by effective overpressure at the wave front.

$$P_d = C_d * p^o$$

$$P_e = p^o + P_d$$

Where,

$P_d$ is dynamic pressure, $p^o$ is peak overpressure, and $C_d$ is drag coefficient ( = 0.1 for sphere, 1.2 for cylinder, 2.0 for square; Lees, 1996).

$$P_{\text{blast}} = -23.8 + 2.92 * \ln P_e$$

Using equations 15 and 16 (Pasman et al. 1992) the probability of damage due to explosion can be computed:

$$P_{\text{blast}} = f_r (P_{\text{blast}})$$

Where $f_r$ represents probit function (function that transforms probit values to percent chance), and $P_e$ is explosion pressure in Pa.

*Missile load*

The impact of missiles on the secondary units is assessed using three parameters:
i) penetration strength, A:

\[ \text{Prob}_A = \frac{(\text{penetration strength} - \text{thickness of vessel})}{\text{penetration strength}} \]  

(17)

ii) impact energy, B:

As reported by Davies (1993) and Lees (1996) about 40-50% of total impact energy is utilized in raising the temperature of the contents of the secondary unit. Hence

\[ \frac{1}{4} \cdot mf \cdot v f^2 = M \cdot C_p \cdot DT \]  

(18)

\[ T_2 = T_1 + DT \]  

(19)

for gases \[ \frac{P_2}{P_1} = \frac{T_1}{T_2} \]  

(20)

for liquefied gas \[ P_2 = n \cdot R \cdot T_2 / V_{vap} + P_1 \]  

(21)

Where, \( V_{vap} = f \cdot V \); \( f \) represents fraction of vapour, \( mf \) the mass of the fragment, and \( vf \) the velocity of the fragment.

\[ \text{Prob}_B = \frac{P_2 - P_{\text{relief}}}{P_{\text{relief}}} \]  

(22)

iii) Probability of collision, C:

The probability of a collision can be computed by dividing the volume of vessel by the total volume of the hemisphere of radius equal to distance between the units including diameter of the vessel.

\[ \text{Prob}_c = \frac{\text{volume of vessel}}{\text{volume of hemisphere}} \]  

(23)

Thus the probability of domino effect due to the impacts of missiles can be computed as:

\[ \text{Prob}_{\text{missile}} = (\text{Prob}_A) \cup (\text{Prob}_B) \cup (\text{Prob}_c) \]  

(24)

\[ \text{Prob}_{\text{missile}} = \text{minimum} \left[ 1, \left( 1 - (1 - \text{Prob}_A)^* (1 - \text{Prob}_B)^* (1 - \text{Prob}_c) \right) \right] \]  

(25)

Finally the probability of occurrence of domino effect will be the sum of the probabilities of each contributing event and can be estimated as;

\[ \text{Prob}_{\text{domino}} = (\text{Prob}_{\text{heat}}) \cup (\text{Prob}_{\text{blast}}) \cup (\text{Prob}_{\text{missile}}) \]  

(26)

\[ \text{Prob}_{\text{domino}} = \text{minimum} \left[ 1, \left( 1 - (1 - \text{Prob}_{\text{heat}})^* (1 - \text{Prob}_{\text{blast}})^* (1 - \text{Prob}_{\text{missile}}) \right) \right] \]  

(27)

\[ \text{Prob}_{\text{domino}} = \text{Prob}_{\text{domino}} \cap \text{Prob}_{\text{primary}} = \text{Prob}_{\text{domino}} \cap \text{Prob}_{\text{primary}} \]  

(28)

Where \( \text{Prob}_{\text{primary}} \) represents probability of the primary event occurrence. The applicability of the scheme can be well understood with the help of a case study. Thus, we are presenting a case study of a petrochemical complex in coming section.

APPLICATION OF DEA - AN EXAMPLE

We now illustrate the use of the two-tier DEA procedure with reference to its application to a petrochemical complex situated at Ramgarh, India. It is a multi-product petrochemical industry engaged in the manufacture of low density polymer (LDP), high density polymer (HDP), caustic soda and other related products.

As a prelude to DEA, a screening was carried out of all the units for their hazard potential. This led to the identification of these five units as highly vulnerable units: general storage farm, cracker unit, poly propylene (PP) plant, low density poly ethylene (LDPE)
plant, and caustic plant. The screening also helped to identify the five most hazardous chemicals: butene, liquefied petroleum gas (LPG), propylene, ethylene and chlorine. The most credible accident scenarios of the primary event were then developed for each unit and a detailed consequence analysis was carried out. The consequences of the primary event were then visualised at the secondary unit. The summary of the study is presented below.

Primary event: general storage farm (butene)

Butene is highly flammable and as it is stored in a liquid form, the most credible accident scenario visualised for this chemical is BLEVE followed by fire ball. The consequence analysis of this scenario, conducted using the software MOSEC, is presented in Table 2. Similar analysis for other units is also presented in Table 2. The potentiality of damage, if an accident occurs in this unit, to other units situated 50 to 100 meters away has been assessed. The resulting domino effects are described below.

Domino effect triggered by the primary event

Chlorine tank (caustic soda unit situated 70 meters away)

Level I study suggests moderate probability of domino effect due to shock wave and thermal effect.

Level II study verifies the same. The probability of domino effect occurrence due to blast waves is 7.5% and due to heat load is ~13% (Table 3).

The scenario for the secondary accident has been visualised as a sudden release of chlorine. It is because large quantity of chlorine is stored in liquid form under high pressure, hence a leak or build-up of high pressure would cause the chemical to be released instantly. The resulting damage would be caused by toxic load with slight overpressure.

General storage farm (second butene tank situated 60 meters away)

Level I study suggests high probability of domino effect.

Level II study suggests 17% probability due to blast wave and 23% chances due to thermal effect (Table 3).

The scenario for the secondary accident in this case has been visualised as: confined vapour cloud explosion (CVCE) followed by fire ball. It is because, heat load would create high internal pressure (about 30% higher than the design value) adding to the already high pressure at which the chemical was stored. As the chemical is highly flammable, it would catch fire soon after release, turning into a fire ball.

LDPE Plant (ethylene tank situated 65 meters away)

Level I study suggests moderate probability of domino effect.

Level II analysis suggests that domino effect probabilities due to the blast and the heat load are 12% and 15% respectively (Table 3). The secondary accident would be of a nature similar to the one that may occur in the butene tank: confined vapour cloud explosion followed by fire ball.

PP Plant (propylene tank situated 90 meters away)
Table 2. Summarized results of consequence analysis of primary event in various units at various locations

<table>
<thead>
<tr>
<th>Unit/Scenario</th>
<th>Damaging Effect</th>
<th>Damaging Potential at Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>75</td>
</tr>
</tbody>
</table>

**LDPE plant (ETHYLENE): CVCE followed by flash fire**

- Heat load (kW/m): 50.55 39.35 27.15 18.73
- Missile Velocity (m/s): 341.52 250.1 185.3 138.75
- Penetration strength (mm): 32 24 16 10 (for 3 kg missile)
- Peak Over pressure (kpa): 115 95 75 63
- Blast wave velocity (m/s): 471 347.3 222.2 162.6

**PP Plant (PROPYLENE): CVCE followed by fire ball**

- Heat load (kW/m): 115.32 78.23 51.4 39.71
- Missile Velocity (m/s): 421.31 348.45 215.3 158.31
- Penetration strength (mm): 43 35 22 14 (for 3 kg missile)
- Peak Over pressure (kpa): 157 129 98 79
- Blast wave velocity (m/s): 757 514.2 368.1 247.3

**General storage farm (BUTENE): BLEVE followed by fire ball**

- Heat load (kW/m): 128.1 85.42 60.3 42.5
- Missile Velocity (m/s): 399.4 287.5 197.1 121.5
- Penetration strength (mm): 37 29 17 11 (for 3 kg missile)
- Peak Over pressure (kpa): 132 98 78 65
- Blast wave velocity (m/s): 648.3 368.1 235.2 188.1

**Cracker Unit (LPG): BLEVE followed by fire ball**

- Heat load (kW/m): 155.5 133.1 87.55 73.23
- Missile Velocity (m/s): --- --- --- ---
- Penetration strength (mm): --- --- --- --- (for 3 kg missile)
- Peak Over pressure (kpa): 145 110 81 68
- Blast wave velocity (m/s): 701 455.6 287.6 204.4

**Caustic Plant (CHLORINE): Instantaneous release followed by dispersion**

- Heat load (kW/m): --- --- --- ---
- Missile Velocity (m/s): --- --- --- ---
- Penetration strength (mm): --- --- --- --- (for 3 kg missile)
- Peak Over pressure (kpa): 95 65 42 35
- Blast wave velocity (m/s): 347.3 188.1 76.6 27.4

---

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Table 3. Results of domino effect analysis due to an accident in General storage farm

<table>
<thead>
<tr>
<th>Unit (Chemicals)</th>
<th>Damaging effects observed</th>
<th>Chances of occurrence of domino effect (%)</th>
<th>Conclusion (secondary accident scenario)</th>
<th>Net probability of occurrence (/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Event: BLEVE followed by fire ball in General storage farm</td>
<td></td>
<td></td>
<td></td>
<td>4.5E-05</td>
</tr>
<tr>
<td>Domino Effect:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caustic plant (Chlorine)</td>
<td>shock wave</td>
<td>7.0</td>
<td>A domino scenario followed by dispersion.</td>
<td>8.5E-06</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>13.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP Plant (Propylene)</td>
<td>shock wave</td>
<td>12.0</td>
<td>A domino scenario followed by BLEVE.</td>
<td>9.6E-06</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>11.0</td>
<td>is BLEVE followed by fire ball.</td>
<td></td>
</tr>
<tr>
<td>LDPE plant (Ethylene)</td>
<td>shock wave</td>
<td>12.0</td>
<td>A domino scenario followed by fire ball/flash fire.</td>
<td>1.1E-05</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>15.0</td>
<td>is BLEVE followed by fire ball/flash fire.</td>
<td></td>
</tr>
<tr>
<td>Cracker plant (LPG)</td>
<td>shock wave</td>
<td>15.0</td>
<td>A domino scenario followed by instantaneous release.</td>
<td>1.4E-05</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>20.0</td>
<td>is an instantaneous release followed by fire ball/flash fire.</td>
<td></td>
</tr>
<tr>
<td>2nd Butene tank (Butene)</td>
<td>shock wave</td>
<td>17.0</td>
<td>A domino scenario followed by fire ball.</td>
<td>1.6E-05</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>23.0</td>
<td>is CVCE followed by fire ball.</td>
<td></td>
</tr>
</tbody>
</table>
Level I study suggests moderate probability of domino effect.

Level II study suggests 12% probability of domino effect due to shock wave and 11% due to heat radiation (Table 3).

The secondary accident scenario likely in the propylene tank is anticipated as; BLEVE followed by fire ball. It is because, the quantity of propylene stored is less and the intensity of damaging events at the location of this unit are also low compared to ethylene but are sufficient to cause sudden release of chemical either through relief valve or through safety valve leading to boiling liquid vapour explosion (BLEVE). The released chemical on meeting an ignition source would lead to fire ball.

Cracker unit (LPG storage situated 60 meters away)
Level I study suggests high probability of domino effect.

Level II study suggests occurrence of domino effect has 15% probability due to shock wave and 20% due to heat load (Table 3).

The domino effect scenario for this unit is visualised as BLEVE followed by fire ball. An intense heat load would develop a high pressure in the LPG bullet and also weaken the strength of vessel which in consequence would lead to sudden release of LPG either through relief valve or through pipe joints as BLEVE. There is lesser probability of CVCE, mainly because in order that a bullet could burst under CVCE excessive pressure must develop in the vessel. This is not possible with the normal storage capacity of a LPG bullet. Of course, the release of LPG on ignition would lead to flash fire or fire ball depending upon the quantity of LPG released.

A simplified block diagram showing the occurrence of domino effect in various units triggered by a primary accident in the butene tank is presented in Figure 7. It is evident that the second butene tank situated near the primary accident site is highly vulnerable. The chlorine tank is comparatively safe.

Similar studies were conducted to analyse the domino effect due to accidents in either one or other of these units PP plant, LDPE plant, cracker unit, and caustic plant. The results are summarised in Tables 4-7.

Consequence analysis covering all the hazardous units reveals that, as far as the primary event is concerned, PP plant has the maximum damage potential as it causes lethal overpressure over the largest area. Risk contours, signifying an individual risk factor greater than $1 \times 10^{-4}$ /yr due to the cumulative effect of the primary and secondary accidents, are plotted over the industry's map in Figure 8. It is evident that an accident in PP plant would endanger an area of more than 300 m radius, while the risk contour for cracker plant would encompass an area of about 200 m radius. An accident in the chlorine storage vessel would bring an area of about 70 m radius under severe risk, the lowest area-of-lethal-impact of the scenarios considered.

In summary, the cracker plant has the potential of causing the most damaging primary accident and also has the maximum probability to lead to domino effect. The intensities of blast wave, missiles, and heat load would be lethal over an area of 200 meters radius if an accident occurs in this plant. The plant has several vulnerable units close to it which would facilitate a long chain of accidents. On the other hand an accident in caustic plant
## Table 4. Results of domino effect analysis due to an accident in PP plant.

<table>
<thead>
<tr>
<th>Unit (Chemicals)</th>
<th>Damaging effects observed</th>
<th>Chances of occurrence of domino effect (%)</th>
<th>Conclusion (secondary accident scenario)</th>
<th>Net probability of occurrence (/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Event</strong>: CVCE followed by flash fire in (Ethylene) FF plant</td>
<td></td>
<td></td>
<td></td>
<td>5.0E-05</td>
</tr>
<tr>
<td><strong>Domino Effect</strong>:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caustic plant (Chlorine)</td>
<td>shock wave</td>
<td>11.0</td>
<td>A domino scenario followed by dispersion</td>
<td>1.3E-05</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>13.0</td>
<td>is instantaneous release</td>
<td></td>
</tr>
<tr>
<td></td>
<td>missile</td>
<td>5.0</td>
<td>followed by dispersion</td>
<td></td>
</tr>
<tr>
<td>General storage (Butane)</td>
<td>shock wave</td>
<td>15.0</td>
<td>A domino scenario by fire ball</td>
<td>1.7E-05</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>14.0</td>
<td>is CVCE followed by fire ball</td>
<td></td>
</tr>
<tr>
<td></td>
<td>missile</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDPE plant (Ethylene)</td>
<td>shock wave</td>
<td>11.0</td>
<td>A domino scenario by fire ball/flash fire</td>
<td>1.4E-05</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>12.0</td>
<td>is BLEVE followed by fire ball/flash fire</td>
<td></td>
</tr>
<tr>
<td></td>
<td>missile</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cracker plant (LPG)</td>
<td>shock wave</td>
<td>8.0</td>
<td>A domino scenario</td>
<td>1.1E-05</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>11.0</td>
<td>is instantaneous release followed by</td>
<td></td>
</tr>
<tr>
<td></td>
<td>missile</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 5. Results of domino effect analysis due to an accident in LDPE plant

<table>
<thead>
<tr>
<th>Unit (Chemicals)</th>
<th>Damaging effects observed</th>
<th>Chances of occurrence of domino effect (%)</th>
<th>Conclusion (secondary accident scenario)</th>
<th>Net probability of occurrence (/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Event: (Propylene)</td>
<td>CVCE followed by fire ball in LDPE plant</td>
<td></td>
<td></td>
<td>3.0E-06</td>
</tr>
<tr>
<td>Domino Effect: Caustic plant (Chlorine)</td>
<td>shock wave</td>
<td>9.0</td>
<td>A domino scenario could be toxic release through relief valve or leakage.</td>
<td>5.4E-07</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General storage (Butane)</td>
<td>shock wave</td>
<td>9.0</td>
<td>A domino scenario could be BLEVE followed by fire ball/flash fire.</td>
<td>8.6E-07</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>13.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>missile</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP Plant (Propylene)</td>
<td>shock wave</td>
<td>7.0</td>
<td>A domino scenario could be CVCE followed by fire ball/flash fire.</td>
<td>7.4E-07</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>11.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>missile</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cracker plant (LPG)</td>
<td>shock wave</td>
<td>6.0</td>
<td>A domino scenario could be a instantaneous release followed either by UVCE or fire ball.</td>
<td>5.6E-07</td>
</tr>
<tr>
<td></td>
<td>heat load</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>missile</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6. Results of Domino effect analysis due to an accident in cracker unit

<table>
<thead>
<tr>
<th>Unit (Chemicals)</th>
<th>Damaging effects observed</th>
<th>Chances of occurrence of domino effect (%)</th>
<th>Conclusion (secondary accident scenario)</th>
<th>Net probability of occurrence (/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Event:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(LPG)</td>
<td></td>
<td></td>
<td></td>
<td>1.0E-04</td>
</tr>
<tr>
<td>Domino Effect:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caustic plant:</td>
<td>shock wave 17.0</td>
<td></td>
<td>A domino scenario is BLEVE followed by dispersion.</td>
<td>3.4E-05</td>
</tr>
<tr>
<td>(Chlorine)</td>
<td>heat load 21.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General storage</td>
<td>shock wave 19.0</td>
<td></td>
<td>A domino scenario is BLEVE followed by flash fire.</td>
<td>3.9E-05</td>
</tr>
<tr>
<td>(Butane)</td>
<td>heat load 25.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP Plant:</td>
<td>shock wave 13.0</td>
<td></td>
<td>A domino scenario is CVCE followed by fire ball/flash fire</td>
<td>2.8E-05</td>
</tr>
<tr>
<td>(Propylane)</td>
<td>heat load 17.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDPE plant:</td>
<td>shock wave 10.0</td>
<td></td>
<td>A domino scenario is CVCE followed by fire ball.</td>
<td>2.4E-05</td>
</tr>
<tr>
<td>(Ethylene)</td>
<td>heat load 15.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7. Results of domino effect analysis due to an accident in caustic plant

<table>
<thead>
<tr>
<th>Unit (Chemicals)</th>
<th>Damaging effects observed</th>
<th>Chances of occurrence of domino effect (%)</th>
<th>Conclusion (secondary accident scenario)</th>
<th>Net probability of occurrence (/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Event (Chlorine)</td>
<td>Instantaneous release followed by dispersion in Caustic soda plant</td>
<td></td>
<td></td>
<td>1.0E-06</td>
</tr>
<tr>
<td>Domino Effect: Cracker plant (LPG)</td>
<td>shock wave 3.0</td>
<td>Very low probability of LPG release followed by flash fire.</td>
<td>3.0E-08</td>
<td></td>
</tr>
<tr>
<td>General storage</td>
<td>shock wave 1.0</td>
<td>Very low probability of (Butane) butane release followed by flash fire.</td>
<td>1.0E-08</td>
<td></td>
</tr>
<tr>
<td>PP Plant (Propylene)</td>
<td>shock wave 7.0</td>
<td>A domino scenario may be propylene release followed by flash fire.</td>
<td>7.0E-08</td>
<td></td>
</tr>
<tr>
<td>LDPE plant (Ethylene)</td>
<td>shock wave 0.00</td>
<td>A domino scenario may be ethylene release followed by flash fire.</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7. Simplified diagram showing locations of units and impact of primary accident (accident in butene tank) over other units.
Figure 8. Plot showing severe risk contour due to PP plant (A), Cracker plant (B), General storage farm (C), 2nd butene tank (D), LDPE plant (E), and Chlorine storage vessel (F).
has the least damage potential and also the least probability of causing secondary accidents.

**SUMMARY and CONCLUSIONS**

1. Study of the probability of occurrence of domino effect and forecasting the impacts if such chain of accident occurs, should be an integral part of any risk assessment study. This is borne out by the history of several past accidents including the most recent one — and one of the biggest ever — which occurred at the HPCL's refinery at Vishakhapatnam, India, on 14 September, 1997.

2. Domino effect can be initiated by five types of primary events - fire, overpressure/shock waves, missiles, toxic load, and a combination of one or more of these.

3. In this paper we have presented details of the mechanisms by which domino effect is initiated by the five types of primary accidents mentioned above. We have then presented models for determining the probabilities of occurrence of these events, developing secondary (and higher order) accident scenarios, forecasting their consequences, and developing disaster prevention/management strategies based on these studies.

4. A two-tier procedure for conducting a typical domino effect study has been presented. The applicability of the procedure has been demonstrated with the help of a case study.

5. One of the interesting and revealing observations that emerges from the case study is that it is not necessary that the unit which has the maximum damage potential (if it meets with an accident) would also have the maximum probability of causing domino effect. It is because the probability of occurrence of domino effect depends not only upon the damage potential of the primary accident but also on a number of other factors such as characteristics of the secondary unit, location of the unit, and site characteristics.

**NOMENCLATURE**

- \( Ar \) = cross sectional area of the unit, \( m^2 \)
- \( Cd \) = drag coefficient
- \( Cp \) = specific heat of the chemical, \( \text{kJ/m}^2/\,^\circ\text{C} \)
- \( DT \) = temperature difference, \( ^\circ\text{C} \)
- \( E_{\text{y max}} \) = maximum allowable stress of the material of construction of the unit, \( \text{N/m}^2 \)
- \( E_y \) = stress developed in unit due to the rise in temperature, \( \text{N/m}^2 \)
- \( f \) = fraction of vapours
- \( Hv \) = heat of evaporation \( \text{kJ/m}^2 \)
- \( K \) = diameter ratio
- \( M \) = mass of the chemical, kg
\( m_f \) = mass of fragment generated due to explosion, kg

\( n \) = number of moles of chemical

\( P \) = pressure, N/m²

\( p^0 \) = peak over pressure, N/m²

\( p \) = over pressure, N/m²

\( Pr \) = Probit value

\( \text{Prob} \) = probability ( /yr)

\( q \) = heat flux, kJ/m²

\( R \) = gas constant (N m⁰°C)

\( T \) = temperature, °C

\( t \) = time, s

\( t_d \) = decay time, s

\( V \) = volume of the unit, m³

\( v_f \) = velocity of fragment generated due to explosion, m/s

\( V_{vap} \) = volume of chemical transformed to vapour, m³

**Symbols**

\( \varepsilon \) = emissivity of the atmosphere

\( \sigma \) = Stefan-Boltzman's constant

\( \gamma \) = Poisson ratio

\( \alpha \) = decay parameter

**Subscript**

1 = initial condition

2 = final condition

blast = shock wave load
d = dynamic
e = explosion

fire = average fire temperature, K

heat = heat load

missile = missile load

relief = pressure relief condition
REFERENCES


Chapter 16

DOMIFFECT (DOMino eFFECT) : A USER-FRIENDLY SOFTWARE FOR DOMINO EFFECT ANALYSIS*

Most of the past risk assessment studies deal with accident in a single industry, more so in one of the units of an industry. However, it is always possible that accident in one unit can cause a secondary accident in a nearby unit which in turn may trigger a tertiary accident, and so on. The probability of occurrence and adverse impacts of such domino or cascading effects are increasing day by day due to increasing congestion in industrial complexes and increasing density of human population around such complexes. This is especially glaring in developing countries. The recent disaster at a refinery in Vishakhapatnam, India, which claimed over 60 lives and damaged property worth Rs 600 million, has brought the damage potential of domino effect into sharp focus.

This paper presents a new computer automated tool DOMIFFECT (DOMino eFFECT) which is the first ever such tool reported for studying domino effects. The package is capable of a) estimating the hazards of fire, explosion, toxic release, or combination of these present in a chemical process industry; b) the damage potential of likely accidents, assessed on the basis of credible scenarios the tool develops; c) the likelihood of second accident being triggered by the first, d) the scenarios of the second accident, their damage potential, and the probability of their causing a third accident (steps similar to a-c above), and so on. The software has been coded in C++ and has

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the attributes i) wide applicability, ii) sophistication, iii) user friendliness, and iv) flexibility for improvement.

Key words: Domino effect, computer software, risk assessment, hazard assessment, consequence analysis.

INTRODUCTION

We have developed techniques and tools for conducting risk assessment in chemical process industries. These include rapid risk assessment using a computer automated tool MAXCRED (Khan and Abbasi, 1996; 1997a), and its advanced version MAXCRED-II (Khan and Abbasi, 1997b), optimising HAZOP (hazard and operability study) procedure (Khan and Abbasi, 1997c), and safety-based design (Khan and Abbasi, 1997d). All these procedures essentially deal with accidents in a single industry, more so in one of the units of an industry. But it is always possible that a major accident in one unit say an explosion or a fire - can cause a secondary accident in a nearby unit which in turn may trigger a tertiary accident. The probability of such domino or cascading effects occurring is increasing day by day with more new industries coming up in already congested industrial areas.

The extent of the likely adverse impacts of such accidents is also increasing rapidly because of increasing demographic pressure which has been forcing people, especially in developing countries, to live close to industrial complexes.

In this paper we present a computer-automated methodology DOMIFFECT (DOMino eFFECT) which enables one to know a) whether domino effects are likely to occur in a given setting, b) if they do what would be the likely accident scenarios, and c) what would be the likely impacts of the different scenarios. Finally, the tool guides us towards strategies needed to prevent domino effects.

Illustrative case studies of some past accidents involving domino effect

When an accident in one unit causes accidents in one or more other units, the phenomena is called cascading effect / domino effect / chain of accidents. We present below a few illustrative case studies of chain of accidents.

At Fyzin (France), in 1966, a fire in one of the storage vessels led to a series of fires and explosions in other vessels (Mahoney, 1990).

At a refinery at Pernis (The Netherlands), in 1968, an overflow of hydrocarbon caused a small explosion. This triggered another small explosion which in turn led to a major explosion with fire, extensively damaging an area of about 300 m. Two people were killed and 85 injured (Lees, 1996).

At Texas city, USA, one of the LPG storage vessels in a petrochemical industry suffered overpressure while it was being filled, due to failure of a pressure gauge and also of a relief valve (Mahoney, 1990). It cracked and leaked LPG. The leak ignited into a massive fire ball, which shattered the vessel, propelling its fragments as missiles. During the next 20 minutes five horizontal bullets and four vertical ones were damaged by missiles. The other two vessels were also damaged in this way.
On 3 July 1987 an explosion occurred inside an ethylene oxide purification column at a chemicals factory at Antwerp, Belgium (Lees, 1996). The explosion was due to decomposition of ethylene oxide. It was accompanied by a fire ball, which started a number of secondary fires. These, together with blasts and missiles, caused extensive damage. Fourteen people were injured.

In November 1984, a major fire and a series of explosions occurred at the PEMEX LPG terminal at San Juan Ixhuatepec, Mexico City (Pietersen, 1986). Some 500 people were killed and the terminal was destroyed. The main LPG storage capacity of 16000 m³ consisted of six spheres and 48 horizontal cylinders. Early in the morning of 18 November the plant was being filled from a refinery 400 km away. At 5.30 a.m. a fall in pressure was registered in the control room and also at pipeline pumping station 40 km distant. It was due to leakage of LPG. The release of LPG continued for some 5-10 minutes. There was a slight wind of 0.4 m/s. The wind and the sloping terrain carried the gas towards the southwest. People in the nearby neighborhood heard the noise of the escape and smelled the gas. When the gas cloud had grown to cover an area, which eyewitnesses put at 250×150 m with a height of 2 m, it caught fire giving a high flame and causing violent ground shock. In another 5 minutes the first BLEVE occurred. About a minute later another explosion occurred. One or two of the smaller spheres suffered BLEVE, giving a fire ball of 300 m diameter. There followed a series of explosions as other vessels, too, had BLEVEs. There were some 15 explosions over a period of an hour and a half. BLEVE occurred of the four smaller spherical vessels and many of the cylindrical vessels. The bursting vessels generated numerous missiles, many of these were heavy (10-14 tons) and went as far as 1 km away. Fifteen of the 48 cylindrical vessels weighing 20 ton became missiles and rocketed over 100 m.

On 23 October 1989 a release occurred in a polyethylene plant at the Phillips company's chemical complex at Pasadena near Houston, Texas (Khan and Abbasi, 1997a). A vapour cloud formed and ignited, giving rise to a massive vapour cloud explosion. There followed a series of further explosions and a fire. Twenty-two persons were killed on the spot and one later from injuries. The number of injured are variously given as 130 and 300.

The mass of gas released was estimated as some 85200 lb of a mixture of ethylene, isobutane, hexane, and hydrogen, which escaped within seconds. A massive vapour cloud formed and moved rapidly downwind. It soon met with a source of ignition.

The TNT equivalent of the resultant explosion was estimated as 2.4 tons. Two other major explosions followed, one when two 20 000 gallon isobutane storage tanks exploded and the other when another polyethylene plant reactor failed catastrophically, some 10-15 minutes and some 25-45 minutes, respectively, after the initial explosion. According to one witness, 10 separate explosions occurred over a 2-hour period. Debris from the explosions was found up to 6 miles from the site.

On September 14, 1997 huge fire and explosions devastated the terminals and storage tanks at the refinery of HPCL (Hindustan Petroleum Corporation Limited) unit at Vishakhapatnam in India. More than 55 persons were killed and dozens of others seriously injured (Hindu, 1997).
Two bodies were found on the upper storey of the administrative block which had collapsed while three more were seen in the debris underneath by a team of reporters who ventured in later in the evening. The building housing the recreation club and canteen were also destroyed.

One of the eight Horton spheres or globe tanks, which contained LPG, crude and kerosene tanks separately, near the main gate of the HPCL refinery, caught fire at 6.40 a.m. and exploded rocking the entire Vishakhapatnam city. The storage tanks were all full, with crude imports unloaded at the HPCL berth just a few days ago. The second sphere exploded 15 minutes later and before noon, the others also caught fire. The blaze spread all over the place. Huge tongues of flame and thick black smoke billowed into the sky and joined the hovering monsoon clouds. There was a sharp shower in the morning and people wearing white shirts saw them turn black with soot. The rain water flooding the road also turned black and murky.

With both the entrances to the refinery blocked by burning tanks, neither the fire tenders nor the officials could enter the premises for several hours. Only when the contents in the tanks were burnt out could they venture in. The death toll could have been higher had the fire started half-an-hour later when the first shift staff would have came in.

Even more significantly as the accident occurred on a Sunday which being a holiday, the administrative personnel, who number over a couple of hundred, were not on duty. There were some contract labourers along with the HPCL personnel in the Crude Distilling Unit which was shut down for routine maintenance work. The shock of the initial explosion made people think an earthquake had occurred. They ran helter-skelter leaving their belongings.

STUDY OF DOMINO EFFECT

Domino effect is observed when accident in one of the units in a chemical process industry causes failure in one or more of the other units, setting off secondary or higher order accidents. For such a chain of accidents to occur it is necessary that a) there are sensitive units within 'striking distance' of the missiles or fires generated by an accident, b) the missiles or fires are powerful enough to cause failure in the units they strike, and c) the probability of both the "hits" occurring, and with sufficient "destructive potential", is high enough to be significant.

Thus to forecast domino effects it is essential to understand factors such as mechanism of accidents, site characteristics, and such interactions which may initiate a chain of accidents. A typical chain of accidents in a chemical process industry is shown in Figure 1, a-c. Figure 1a shows building-up of high pressure in the vessel which causes explosion and fire, generating heat load, shock waves, and missiles. The nearby unit (sphere, Figure 1b) is damaged, in turn generating fresh heat load, shock waves, and missiles. The chain continues through to the third unit (Figure 1c) In a real-life situation such a cascading effect would propagate as long as no more units are present within the danger zone created by the previous accidents.

Domino effect can be triggered by three types of primary accidents:

1) involving fire,
2) involving explosions leading to
Figure 1. Typical chain of accidents in a chemical process industry
- blast wave effect;
- missiles effect;

3) involving a combination of fire and explosion.

To forecast the occurrence and assess the consequences of domino effect, deterministic models in conjunction with probabilistic analysis have to be used (Latha et al., 1992). Probabilistic models based on previous histories are useful in the assessment of event frequencies', equipment reliability, direction of projectiles' movement, etc. The physical and chemical processes, namely leak development, chemical discharge and dispersion, cloud formation, explosion, fire, vessel fracture, and related phenomena, can best be assessed by deterministic approaches.

Study of domino effect also requires an understanding of transient interchange of damage load (fire and explosion) between the initiator and receiver, and mechanics of vessel failure (Bagster and Pitblado, 1991). Figure 2 shows mechanism of domino effect modelling in chemical process industries.

**Domino effect triggered by fire**

Fire is caused when a chemical undergoes uncontrolled oxidation in the presence of air liberating heat. Important aspects of modelling domino/cascade effects due to fire (Figure 3) include prediction of flame heights, flame merging phenomena, and the effect of wind on flame tilt and length (Moorehouse, 1982; Considine, 1984; Latha et al. 1992).

The reception of thermal radiation by a target is most important for quantification of domino effects. It depends on the atmospheric transmittivity and the geometrical view factor. The latter depends not only on the shape of the flame, the distance, and position of the receiver but also on its orientation.

Many chemical plant installations are equipped with pressurised (liquefied) gas-filled tanks and storage vessels and study of their fire engulfment is important for the quantification of domino effects. The engulfment can be partial or total. The heat transfer and geometry analysis of engulfment of liquid-or vapour-filled vessels have been reported by Ramskill (1987), and Beynon et al. (1988).

To model the fire as an initiating event (Figure 3) following aspects, have to be taken into consideration:

I. transient nature of incident flame temperature, velocity, and emissivity:

II. various vessel shapes, e.g., cylindrical, spherical, cuboid, in vertical or horizontal disposition:

III. existence of several temperature zones in the fire-engulfed vessels:

IV. complex modes of heat transfer: fire to tank through radiation and convection; tank wall external to internal surfaces by conduction; tank inner wall to the vapour phase through radiation and convection; vapour to liquid phase by radiation and convection; and tank wall to the liquid phase by convection (natural and forced):

V. transfer of material from liquid to vapour phase during boiling (nucleate or film process) and from vapour to atmosphere during vent operation.
Figure 2. The mechanism of domino/cascading effect pertaining to modelling of chain of accidents in chemical process industries
Figure 3. Procedure for domino effect analysis triggered by fire
**Domino effect triggered by explosion**

Generally an explosion generates three damaging events (henceforth referred as characteristics of explosion):

i) blast waves/overpressure,

ii) heat load, and

iii) missiles, which when encountered by the secondary unit can lead to failure of unit, either through rupture, uprooting or through strain failure (Figure 4).

The term 'blast wave' is used here to mean the shock wave caused by an explosion. The blast wave from all chemical explosions has a definite and measurable pattern. Upon detonation a sudden and violent release of energy causes the surrounding air pressure to rise rapidly creating a region of positive pressure known as "overpressure". As the blast wave moves away from its source at high velocity the overpressure increases sharply to a peak value, known as the peak overpressure, and then gradually reduces. The overpressure phase is followed by a region of negative pressure or underpressure.

Damage and injury as a result of blast wave is largely a consequence of diffraction loading. Diffraction loading is related to the peak overpressure of a blast wave as it passes over and around an object or structure. Peak overpressure refers to the pressure above ambient at a given location (often termed side-on overpressure). Diffraction loading refers to the force exerted on an object or structure during blast wave envelopment. The loading consists of two components

1. resulting from the pressure differential that exists between the front and the back of an object/structure prior to envelopment, and

2. static loading ('cruising' forces) due to the pressure differential between internal and external environments.

Blast wave damage is also a function of rate of pressure rise and wave duration. As a consequence of this, impulse is also used as a measure of blast damage. Impulse is a function of both overpressure and wave duration. The characteristics of blast wave as damaging event have been discussed by Maurer (1977), Baker et al. (1983), Martinsen et al. (1986), Medard (1989), Prugh (1991), Greenbook (1992) Venerate et al. (1993), Van den Berg and Lennoy (1993), Davies (1993), and Khan and Abbasi (1996).

The fragments which are generated as a result of explosion, can cause significant damage (Figure 4). Energy delivered to fragments from blast waves cause the former to become airborne and act as missiles. Such missiles could be either primary or secondary. Primary missiles consist of casing and/or container fragments from the exploded vessel. The secondary missiles consist of fragments from objects located close to the explosion source which have interacted with the blast wave. The characteristics of the missiles - primary or secondary - which are important in the study of domino effect are:

i) velocity ,

ii) shape,

iii) kinetic energy ,

iv) penetrative ability ,
Figure 4. Procedure of domino effect analysis triggered by explosion
v) direction.

The history of past accidents (Kletz, 1985; Marshal, 1987; Raghavan and Swaminathan, 1996; Lees, 1996; Khan and Abbasi, 1996; 1997a; 1997b; Hindu, 1997) reveals that more often than not industrial accidents generate a combination of different impacts (explosion, fire and toxic release) rather than a single impact. Thus to study domino effect, the probability of occurrence of each type of primary impact (heat load, blast wave, and missiles) should be estimated and combined according to the anticipated sequence of events in order to forecast the nature and intensity of the secondary accident. (Khan and Abbasi, 1997a, 1997b).

THE DOMIFFECT SOFTWARE

We have developed DOMIFFECT (DOMino eFFECT) as one of the tools for conducting risk assessment in chemical process industries, sequence of steps is shown in Figure 5. DOMIFFECT is menu-driven and interactive, capable of the following:

- estimation of all possible hazards from toxic release to explosion;
- handling of interaction among different accidental events (generation of domino or cascading accident scenarios);
- estimation of domino effect probability;
- estimation of domino effect consequences.

The software incorporates state-of-the-art models for studying a) the hazards of fire, explosion, toxic release, or combination of these present in a chemical process industry; b) the damage potential of likely accidents, assessed on the basis of credible scenarios the tool develops; c) the likelihood of second accident being triggered by the first, d) the scenarios of the second accident, their damage potential, and the probability of their causing a third accident (steps similar to a-c above), and so on. A major feature of DOMIFFECT is the module automatic analysis. This module uses a knowledge-base built into DOMIFFECT, estimates the detailed consequences, and checks the probability of occurrence of secondary or higher order accidents at different locations.

DOMIFFECT is a PC-based software with object oriented architecture coded in C++. It consists of six main modules DATA, ACCIDENT SCENARIO, ANALYSIS, DOMINO, GRAPHICS and USER INTERFACE. The Architecture and message flow sequence of DOMIFFECT is shown in Figure 6. Each module consists of several sub-modules and functions.

Data, accident scenario, and analysis modules

The data module is similar to the one incorporated in our package MAXCRED-II (Khan and Abbasi, 1997c, 97e). Accident scenario module also has several features similar to the ones included in MAXCRED II, with the following additions:

i) automatic scenario generation sub-module of DOMIFFECT consists of more elaborate knowledge-base (implemented in terms of rule network; Figure 7) than the corresponding MAXCRED-II sub-module

ii) a different and faster inference engine (combination of forward and backward chaining; Figure 8) is used for retrieving the knowledge from knowledge-base;
Figure 5. Algorithm of DOMIFFECT
Figure 6. Architecture and message flow diagram of DOMIFFECT
Figure 7. Typical rule network for automatic accident scenario generation module
Figure 8. Inference engine of DOMIFFECT to decide the accident scenario
iii) user-defined scenario generation sub-module consists of more advanced models for explosion and fire. It also treats gaseous dispersion in much more elaborate fashion incorporating density effects (heavier than air), atmospheric conditions, and terrain characteristics (Tables 1-3).

The analysis module has the features contained by the corresponding module of MAXCRED-II. In addition it contains newer models (Tables 1-3).

**Domino module**

It analyse the damage potential of the primary event at the point of location of the secondary unit and checks for the likelihood of the occurrence of the secondary accident. If the probability of the secondary accident is sufficiently high then the appropriate accident scenarios are developed and analysed for consequences.

This module has an independent set of information which should be provided by the user. The information pertain to the operational details of the secondary unit, chemicals used, meteorological conditions, and topological characteristics. This module consists of various sets of mathematical models for estimating the damage consequences (Tables 1-3), and probability of occurrence of secondary accidents due to the effect of the primary ones (Table 4).

The main Domino module is classified into four sub-modules based on different type of accident initiating events: heat_load, blast_load, and missile_load. The probability of domino effect is estimated through $F_{\text{prob}}$ function defined in main Domino module and inherited by all submodules. The models used, and the framework within which they are to be used, has been described by us in detail elsewhere (Khan and Abbasi, 1997h). Relevant probit equations are recapitulated below in brief.

**Heat load**

i) Failure of the second vessel due to high pressure build-up caused by the primary accident.

The probability of secondary accident due to heat absorbed by the chemical in the target vessel:

$$0.40 \cdot q \cdot Ar = M \cdot Cp \cdot DT$$

where, $Cp$ represents specific heat of chemical ($kJ/m^2\cdot^\circ C$), DT is temperature difference, $M$ is mass of chemical (kg), $Ar$ is area of vessel ($m^2$), and $q$ is heat load incident over the vessel.

At temperature $T_2$, the fraction of vapour generated is (Kayes, 1986; Greenbook, 1992):

$$f = 1 - \exp(-Cp \cdot (T_2 - T_1)/Hv)$$

and

$$V_{vap} = f \cdot V$$

where, $Hv$ is heat of evaporation ($kJ/kg$), $V$ is total volume of chemical ($m^3$), $f$ is fraction of vapour and $V_{vap}$ is volume of vapour generated ($m^3$).

The pressure developed in the vessel:
<table>
<thead>
<tr>
<th>Event</th>
<th>Model incorporated</th>
<th>Important references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxic release</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light gas</td>
<td>Gaussian dispersion model with Erbink modification</td>
<td>Greenberg and Cramer, 1992</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy gas</td>
<td>Box model, modified plume path theory for heavy gas</td>
<td>Deaves, 1992; Khan and Abbasi, 1997f, 1997g</td>
</tr>
</tbody>
</table>
### Table 2 List of different Explosion models used in analysis module of DOMIPFECT

<table>
<thead>
<tr>
<th>Event</th>
<th>Model incorporated</th>
<th>Important references</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPLOSION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BLEVE</td>
<td>thermodynamic and heat transfer models</td>
<td>Pietersen, 1990, Pasman et al., 1992</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prugh, 1991, Venerate et al., 1993</td>
</tr>
<tr>
<td>VCE</td>
<td>vapor cloud explosion</td>
<td>Ven den Berg and Lennoy, 1993; Prugh, 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prugh, 1992; Lees, 1996</td>
</tr>
<tr>
<td>CVCE</td>
<td>vapor cloud explosion in confinement (vessel or building)</td>
<td>Singh, 1988; Pietersen, 1990; Lees, 1996,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pritchard, 1989; CCPS, 1994</td>
</tr>
</tbody>
</table>
Table 3  List of different fire models used in analysis module of DONIFFECT

<table>
<thead>
<tr>
<th>Event</th>
<th>Model incorporated</th>
<th>Important reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash fire</td>
<td>flare model, fire torch and spontaneous combustion</td>
<td>Hayes, 1986; Greenberg and Crammer, 1992; OIEA, 1994</td>
</tr>
<tr>
<td>Pool fire</td>
<td>combustion of liquid pool</td>
<td>Roberts, 1983; Mourehouse, 1982; Davies, 1993; Greenbook, 1992</td>
</tr>
<tr>
<td>Fire ball</td>
<td>spontaneous combustion of vapor cloud</td>
<td>Roberts, 1983; Davies, 1993; Prugh, 1994</td>
</tr>
</tbody>
</table>
Table 4 List of different models used in domino module of DOMIFPECT

<table>
<thead>
<tr>
<th>Event</th>
<th>Model incorporated</th>
<th>Important references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat load</td>
<td>thermodynamic models, fluid expansion models, probit function, heat transfer models.</td>
<td>Pietersen, 1990; Bagster and Pitblado, 1990; Prugh, 1994; Latba et al. 1992; Khan and Abbasi, 1997h</td>
</tr>
<tr>
<td>Blast wave load</td>
<td>shock wave model, pressure-impulse model pressure loading, pressure-temperature interaction, empirical probit models.</td>
<td>Pritchard, 1989; Pietersen, 1990; Davies, 1993; Khan and Abbasi, 1997h; Lees, 1996</td>
</tr>
<tr>
<td>Missile load</td>
<td>missile impact model, thermodynamic models, heat transfer models, and empirical models for probability estimation.</td>
<td>Bowen, 1988; Davies, 1993; Khan and Abbasi, 1997h</td>
</tr>
</tbody>
</table>
If $P_2$ is greater than the relief pressure, it may lead to release of the chemical contained in the vessel and if it is greater than the design pressure then the vessel may burst. The degree of excess pressure and the mechanical properties of the material of construction of the vessel would bear upon the severity of the secondary accident. The probability of an accident due to rise in pressure is given by:

$$\text{Prob}_{\text{heat}} = \frac{(P_2 - P_{\text{relief}})}{P_{\text{relief}}}$$  \hspace{1cm} (5)

ii) Vessel rupture due to material failure.

The second vessel may fail due to loss in the strength of the material of construction. The probability of this occurrence can be computed using maximum strain theory (Bhattacharya, 1986). Heat load developed due to fire would raise the temperature of the vessel wall (radiation is the dominant mode of the heat transfer). This rise in the temperature will reduce the maximum allowable stress of the vessel. This phenomena is quantified by:

$$T_2 = \left[ \left( \varepsilon^* \sigma^* T_{\text{fire}}^4 - q \right) / (\varepsilon^* \sigma^*) \right]^{1/4}$$  \hspace{1cm} (6)

These authors have developed an empirical equation to quantify the impact of temperature on the maximum allowable stress, taking into consideration the properties of 15 common materials of construction over the temperature range 50 to 1200 °C.

$$E_{y_{\max}} = \text{function (temperature)}$$

$$E_{y_{\max}} = 1\times10^8 \left(1.858 - 0.0062T_2 + 1.691E-05 \times T_2^2 - 1.959E-08 \times T_2^3\right)$$  \hspace{1cm} (7)

$E_{y_{\max}}$ is maximum allowable stress in N/m² (property of the material of construction), and $T$ is temperature in °C. The stress developed in the vessel due to rise in the internal pressure of the vessel is quantified using following equation (Bhattacharya, 1986)

$$E_y = P_2 \left[(1-\gamma) + 2K(1+\gamma)/(K^2-1)\right]$$  \hspace{1cm} (8)

$\gamma$ denotes Poisson ratio, $K$ denotes diameter ratio, $P_2$ is Pressure in the vessel in N/m².

The probability of vessel failure due to failure of the material of construction is estimated as:

$$\text{Prob}_{\text{heat}} = \frac{E_{y_{\max}}}{E_y}$$  \hspace{1cm} (9)

Finally the probability of secondary accident due to heat load is computed using the function:

$$\text{Prob}_{\text{heat}} = \text{Prob}_{\text{heat1}} \cup \text{Prob}_{\text{heat2}}$$  \hspace{1cm} (10)

$$\text{Prob}_{\text{heat}} = \text{minimum[1, \{1-(1-\text{Prob}_{\text{heat1}})*(1-\text{Prob}_{\text{heat2}})\}]}$$  \hspace{1cm} (11)

Blast load (overpressure)

When a blast wave developed due to an explosion hits an object, it causes a diffraction/drag type of impact. The damage likely due to such impact is measured by effective overpressure at the wave front.

$$P_d = C_d \times P^o$$  \hspace{1cm} (12)
\[ P_e = p^0 + P_d \]  

Where,

\( P_d \) is dynamic pressure, \( p^0 \) is peak overpressure, and \( C_d \) is drag coefficient (\( = 0.1 \) for sphere, \( 1.2 \) for cylinder, \( 2.0 \) for square; Lees, 1996).

\[ P_{blast} = -23.8 + 2.92 \ln P_e \]  

Using equations 14 and 15 (Pasman et al., 1992) the probability of damage due to explosion can be computed:

\[ \text{Prob}_{\text{blast}} = f_r\left(P_{\text{blast}}\right) \]  

\( f_r \) represents probit function (function that transform probit values to percent chance), and \( P_e \) is explosion pressure in Pa.

**Missile load**

The impact of missiles on the secondary units is assessed using three parameters:

i) penetration strength, \( A \):

\[ \text{Prob}_A = \frac{\text{penetration strength-thickness of vessel}}{\text{penetration strength}} \]  

ii) impact energy, \( B \):

As reported by Davies (1993) and Lees (1996) about 40-50% of total impact energy is utilised in raising the temperature of the contents of the secondary unit. Hence

\[ \frac{1}{4} m_f v_f^2 = M^*C_p^*D_T \]  

\[ T_2 = T_1 + D_T \]  

for gases \( \frac{P_2}{P_1} = \frac{T_1}{T_2} \)  

for liquefied gas \( P_2 = n^*R^*T_2 / \nu_{\text{vap}} + P_1 \)  

\[ \nu_{\text{vap}} = \frac{f^*V_f}{f} \]  

\( f \) represents fraction of vapour, \( m_f \) the mass of the fragment, and \( v_f \) the velocity of the fragment.

\[ \text{Prob}_B = \frac{P_2 - P_{\text{relief}}}{P_{\text{relief}}} \]  

iii) Probability of collision, \( C \):

The probability of a collision can be computed by dividing the volume of vessel by the total volume of the hemi-sphere of radius equal to distance between the units including diameter of the vessel.

\[ \text{Prob}_C = \frac{\text{volume of vessel}}{\text{volume of hemisphere}} \]  

Thus the probability of domino effect due to the impacts of missiles can be computed as:

\[ \text{Prob}_{\text{missile}} = (\text{Prob}_A) \cup (\text{Prob}_B) \cup (\text{Prob}_C) \]  

\[ \text{Prob}_{\text{missile}} = \text{minimum} \left[ 1, (1 - (1 - \text{Prob}_A)(1 - \text{Prob}_B)(1 - \text{Prob}_C)) \right] \]  

Finally the probability of occurrence of domino effect will be the sum of the probabilities of each contributing event and can be estimated as:

\[ \text{Prob}_{\text{domino}} = (\text{Prob}_{\text{heat}}) \cup (\text{Prob}_{\text{blast}}) \cup (\text{Prob}_{\text{missile}}) \]
\[
\text{Prob}_{\text{domino}} = \text{minimum}(1, (1 - \text{Prob}_{\text{heat}})^r (1 - \text{Prob}_{\text{blast}})^r (1 - \text{Prob}_{\text{missile}})^r)
\]  
(26)

\[
\text{Prob}_{\text{domino}} = \text{Prob}_{\text{domino}} \cap \text{Prob}_{\text{primary}} = \text{Prob}_{\text{domino}} * \text{Prob}_{\text{primary}}
\]  
(27)

Where \(\text{Prob}_{\text{primary}}\) represents probability of the primary event occurrence. The applicability of the scheme can be well understood with the help of a case study. Thus, we are presenting a case study of a petrochemical complex in coming section.

**Graphics and user interface module**

This module enables DOMIFFECT to execute site drawings and draw damage/risk contour maps.

The user interface module of DOMIFFECT handles data file, scenario file, output file, and flow of information. This module works as 'information manager': it provides the necessary information to each module and sub-module for carrying out the desired operations, and stores the results in appropriate slots.

**APPLICATION OF DOMIFFECT - AN EXAMPLE**

**Preamble**

In a chemical industry butadiene \((\text{C}_4\text{H}_6)\) and ammonia \((\text{NH}_3)\) are stored (in liquefied state) at -25 \(^\circ\)C, -55 \(^\circ\)C, and 3.5 atm, 6.5 atm, respectively. The storage capacities the two tanks are 10 metric ton, and of 5 metric ton respectively. The two units are spaced 75 m away from each other. DOMIFFECT was used to forecast the accidents likely and their consequences in this setting.

**Results**

The storage units pose three types of hazard: i) explosion hazard due to butadiene and ammonia, ii) fire hazard due to butadiene, and iii) toxicity hazard due to ammonia.

The plausible accident scenarios envisaged in the storage units are:

**Scenario 1**

Unconfined vapour cloud explosion (UVCE) occurs in the butadiene unit accompanied by a pool fire. This shall happen if a small leak in the storage vessel releases the contents at moderate flow rate and forms a vapour cloud in the atmosphere which on ignition leads to UVCE. Due to the heat generated by UVCE or by an external source of ignition, the remaining material in the vessel gives up in flame causing a pool fire. The shock wave generated by UVCE and the heat load built up by the pool fire can damage the neighbouring ammonia storage vessel and trigger secondary and higher order accident.

**Scenario 2**

An excessive pressure development in the storage vessel of butadiene leads to confined vapour cloud explosion (CVCE). The vapour cloud thus generated on ignition turns into a fire ball and consequently damages the other storage vessel (ammonia storage vessel).

**Scenario 3**

An excessive by high pressure development in the storage vessel of butadiene leads to BLEVE. The unburned vapour cloud thus formed on ignition leads to a fire ball. As the damage potential of a BLEVE is expected to be less severe compared to CVCE or UVCE, the ammonia storage vessel would not be affected.
**Scenario 4**

An instantaneous release of ammonia.

**Analysis**

A UVCE as per scenario 1 would give rise to heat radiation effects, shock waves, and missiles. In addition there would be secondary impact of burning of released material in the dike/vessel which would again lead to additional heat load. In scenario 1, missile effect is not significant (Table 5). However, shock waves of intensity high enough to damage all objects coming in their way would be occurring in an area of ~250 m radius. The combined impact of heat radiation, UVCE, and pool fire would be lethal over an area of ~500 m radius. The damage contour for more than 50% probability of damage/lethality would be extended over an area of ~500 m radius (Table 6). This scenario has 29% probability of causing secondary accident (release of ammonia), which may propel the gas in lethal concentrations over an area of ~500 m radius.

The CVCE in butadiene tank as per scenario 2 would generate shock waves and missile effects (Table 7). These would cause damage over a wider area than likely as per scenario 1 (Table 8). The butadiene released from the vessel would form a vapour-air mixture which on ignition would cause fire ball lethally effecting an area of ~500 m. The probability of a secondary accident (release of ammonia) due to this accident is about 47%. The secondary accident would cause build-up of ammonia over a wide area. All-in-all a region of ~700 m radius would be at great risk due to heat load, shock waves, and toxic load (Table 8).

The DOMIFFECT outputs of scenarios 3 and 4 are presented in Tables 9 and 10 respectively. As per scenario 3 BLEVE would generate shock waves as well as missiles. In addition, there would be secondary impact of the released material getting ignited and forming fire ball thereby generating additional heat load. The output of DOMIFFECT for this scenario is presented in Table 9. The lethal impact of shock-waves, heat load, and missiles would go up to a radius of ~150 m (Table 11). As per scenario 4 (Tables 10 and 12), a lethal toxic load would be persistent over an area of ~500 m radius. The probability of secondary impacts (domino effect) is low in both the scenarios. The damage potential (50% probability of damage) of scenarios 3 and 4 as a function of distance from accident epicentre is presented in Tables 11 and 12 respectively.

**DISCUSSION**

Scenario 2 is the one most likely to cause domino effects as missiles, shock waves, and radiation loads would be generated simultaneously and units dealing with hazardous chemicals (flammable and toxic materials) are situated within the striking distance of the impact area of this scenario. Scenario 2 also represents the worst likely disaster within the realm of credibility as it has the largest area-of-lethal-impact (shock waves, lethal heat load, and lethal concentration of ammonia over an area of ~1000 m). Scenario 1 is also likely to cause secondary accidents but its adverse impacts would be lesser than of scenario 2.

In conclusion, DOMIFFECT reveals that, scenario 2 is the worst as far as the largeness of its impact area is concerned as well as in terms of its potentiality of causing secondary accidents. It follows that all strategies for minimising or eliminating risk should be based on
Table 5. The result of DOMIFFECT for accident scenario 1

**DOMIFFECT**

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Khan & S A Abbasi, Pondicherry-605 014, India

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Result for scenario UVCE followed by Pool fire with domino analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Event</strong></td>
<td></td>
</tr>
<tr>
<td>Explosion : UVCE</td>
<td></td>
</tr>
<tr>
<td>Total energy released by explosion</td>
<td>(kJ) : 4.9E+06</td>
</tr>
<tr>
<td>Peak over pressure</td>
<td>(kPa) : 224.6</td>
</tr>
<tr>
<td>Variation of over pressure in air</td>
<td>(kPa/s) : 84.3</td>
</tr>
<tr>
<td>Shock velocity of air</td>
<td>(m/s) : 450.9</td>
</tr>
<tr>
<td>Duration of shock wave</td>
<td>(ms) : 35</td>
</tr>
<tr>
<td><strong>Missile characteristics:</strong></td>
<td></td>
</tr>
<tr>
<td>Kinetic energy associated with missile</td>
<td>(kJ) : 1.49E+05</td>
</tr>
<tr>
<td>Initial velocity of fragment</td>
<td>(m/s) : 156.3</td>
</tr>
<tr>
<td><strong>Penetration ability at distance of 250 meter:</strong></td>
<td></td>
</tr>
<tr>
<td>Concrete structure</td>
<td>(m) : 0.0340</td>
</tr>
<tr>
<td>Brick structure</td>
<td>(m) : 0.0434</td>
</tr>
<tr>
<td>Steel structure</td>
<td>(m) : 0.0044</td>
</tr>
<tr>
<td><strong>Fire : Pool fire</strong></td>
<td></td>
</tr>
<tr>
<td>Radius of the pool fire</td>
<td>(m) : 247.0</td>
</tr>
<tr>
<td>Burning area</td>
<td>(sq.m) : 191781.8</td>
</tr>
<tr>
<td>Burning rate</td>
<td>(kg/min) : 1574.8</td>
</tr>
<tr>
<td>Heat flux</td>
<td>(kJ/sq.m) : 932</td>
</tr>
<tr>
<td><strong>Secondary Effect</strong></td>
<td></td>
</tr>
<tr>
<td>Domino Checking</td>
<td></td>
</tr>
<tr>
<td>Distance of study for secondary unit</td>
<td>(m) : 75.0</td>
</tr>
</tbody>
</table>

---

Contd..
Domino effect due to heat load:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat load (kJ/sq m)</td>
<td>215</td>
</tr>
<tr>
<td>Probability of domino effect</td>
<td>6%</td>
</tr>
</tbody>
</table>

Domino effect due to over pressure:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak over pressure (kPa)</td>
<td>72</td>
</tr>
<tr>
<td>Probability of domino effect</td>
<td>23%</td>
</tr>
</tbody>
</table>

Domino effect due to missile:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missile velocity (m/s)</td>
<td>44.3</td>
</tr>
<tr>
<td>Probability of domino effect</td>
<td>2%</td>
</tr>
</tbody>
</table>

Domino analysis: Toxic release and dispersion

Box continues model: Elevated source

Concentration at distance of 200 (m), (kg/cu.m): 6.65111E-05

Heavy gas plume Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground level concentration of plume (kg/cu.m)</td>
<td>6.61186E-05</td>
</tr>
<tr>
<td>Ground level concentration on plume axis (kg/cu.m)</td>
<td>8.24479E-04</td>
</tr>
<tr>
<td>Width of plume (m)</td>
<td>2.50936E+02</td>
</tr>
<tr>
<td>Maximum ground level concentration (kg/cu.m)</td>
<td>3.49569E+01</td>
</tr>
</tbody>
</table>
Table 6. Probabilities of different extent of damages at different distances from the epicentre of the accident for scenario 1

<table>
<thead>
<tr>
<th>Damaging effect</th>
<th>at a distance of (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td>50% lethality by heat load</td>
<td>100%</td>
</tr>
<tr>
<td>50% injury due to shock load</td>
<td>100%</td>
</tr>
<tr>
<td>50% damage due to missile effect</td>
<td>34%</td>
</tr>
<tr>
<td>50% lethality due to toxic load</td>
<td>100%</td>
</tr>
</tbody>
</table>
Table 7. The result of DOMIFFECT for accident scenario 2

DOMIFFECT

: I Khan & S A Abbas, Pondicherry-605 014, India

Result for scenario CVCE followed by Fire ball with domino analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Event</strong></td>
<td></td>
</tr>
<tr>
<td>Explosion : CVCE</td>
<td></td>
</tr>
<tr>
<td>Energy released during explosion (kJ)</td>
<td>2.4E+08</td>
</tr>
<tr>
<td>Peak over pressure (kPa)</td>
<td>626.4</td>
</tr>
<tr>
<td>Variation of over pressure in air (kPa/s)</td>
<td>420.4</td>
</tr>
<tr>
<td>Shock velocity of air (m/s)</td>
<td>763.6</td>
</tr>
<tr>
<td>Duration of shock wave (ms)</td>
<td>41</td>
</tr>
<tr>
<td><strong>Missile result</strong></td>
<td></td>
</tr>
<tr>
<td>Kinetic energy associated with fragment (kJ)</td>
<td>3.9E+06</td>
</tr>
<tr>
<td>Initial velocity of fragment (m/s)</td>
<td>252.9</td>
</tr>
<tr>
<td>Penetration at distance of 250 meter :</td>
<td></td>
</tr>
<tr>
<td>Concrete structure (m)</td>
<td>0.127</td>
</tr>
<tr>
<td>Brick structure (m)</td>
<td>0.162</td>
</tr>
<tr>
<td>Steel structure (m)</td>
<td>0.024</td>
</tr>
<tr>
<td><strong>Fire : Fire ball</strong></td>
<td></td>
</tr>
<tr>
<td>Radius of the fire ball (m)</td>
<td>157.4</td>
</tr>
<tr>
<td>Duration of the fire ball (s)</td>
<td>64</td>
</tr>
<tr>
<td>Energy released by fire ball (kJ)</td>
<td>6.4E+07</td>
</tr>
<tr>
<td>Radiation heat flux (kJ/sq.m)</td>
<td>1435.6</td>
</tr>
<tr>
<td><strong>Secondary event</strong></td>
<td></td>
</tr>
<tr>
<td>Domino checking</td>
<td></td>
</tr>
<tr>
<td>Distance of secondary event</td>
<td>75.00</td>
</tr>
</tbody>
</table>

Contd...
Heat load:

\[
\text{Heat load } (kJ/m^2) : 545 \\
\text{Probability of domino event due fire } (%) : 14
\]

Domino effect due to over pressure:

\[
\text{Peak over pressure } (kPa) : 95 \\
\text{Probability of domino effect due to explosion is } (%) : 35
\]

Domino effect due to missile:

\[
\text{Missile velocity } (m/s) : 115.2 \\
\text{Probability of domino effect due to missile } (%) : 6.34
\]

Domino analysis: Toxic release and dispersion

Box instantaneous model: Elevated source

\[
\text{Concentration at distance of 200 (m), } (kg/cu.m) : 3.45231E-04
\]

Heavy gas puff Characteristics

\[
\text{Ground level concentration of puff } (kg/cu.m) : 3.45231E-04 \\
\text{Ground level concentration on puff axis } (kg/cu.m) : 3.45231E-03 \\
\text{Cloud radius } (m) : 1.16753E+02 \\
\text{Maximum distance traveled by the cloud } (m) : 7.87457E+02 \\
\text{Maximum ground level concentration } (kg/cu.m) : 4.3
\]
Table 8. Probabilities of different types of damages at different distances from the epicentre of the accident for scenario 2

<table>
<thead>
<tr>
<th>Damaging effect</th>
<th>at a distance of (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td>50% lethality by heat load</td>
<td>100%</td>
</tr>
<tr>
<td>50% injury due to shock load</td>
<td>100%</td>
</tr>
<tr>
<td>50% damage due to missile effect</td>
<td>50%</td>
</tr>
<tr>
<td>50% lethality due to toxic load</td>
<td>100%</td>
</tr>
</tbody>
</table>
Table 9. The result of DOMIFFECT for accident scenario 3

DOMIFFECT

; K. Khan & S A Abbe, Pondicherry-605 014, India

Result for scenario BLEVE followed by fire ball with domino analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Event</strong></td>
<td></td>
</tr>
<tr>
<td>Explosion : BLEVE</td>
<td></td>
</tr>
<tr>
<td>Total energy released</td>
<td>(kJ) : 12890.0</td>
</tr>
<tr>
<td>Peak over pressure</td>
<td>(kPa) : 65.8</td>
</tr>
<tr>
<td>Variation of over pressure in air</td>
<td>(kPa/s) : 0.67</td>
</tr>
<tr>
<td>Shock velocity of air</td>
<td>(m/s) : 389.0</td>
</tr>
<tr>
<td>Duration of shock wave</td>
<td>(ms) : 300</td>
</tr>
<tr>
<td>No missile effect</td>
<td></td>
</tr>
<tr>
<td>Fire : Fire ball</td>
<td></td>
</tr>
<tr>
<td>Radius of the fire ball</td>
<td>(m) : 88.1</td>
</tr>
<tr>
<td>Duration of the fire ball</td>
<td>(s) : 36</td>
</tr>
<tr>
<td>Energy released by fire ball</td>
<td>(kJ) : 1.0E+06</td>
</tr>
<tr>
<td>Radiation heat flux</td>
<td>(kJ/sq.m) : 745.6</td>
</tr>
<tr>
<td><strong>Secondary Event</strong></td>
<td></td>
</tr>
<tr>
<td>Domino Checking</td>
<td></td>
</tr>
<tr>
<td>Distance of Study</td>
<td>: 75.0</td>
</tr>
<tr>
<td>Heat load :</td>
<td></td>
</tr>
<tr>
<td>Heat load</td>
<td>(kJ/sq m) : 156</td>
</tr>
<tr>
<td>Chances of domino event due fire</td>
<td>(%) : 2</td>
</tr>
<tr>
<td>Domino effect due to over pressure</td>
<td></td>
</tr>
<tr>
<td>Peak over pressure</td>
<td>(kPa) : 34</td>
</tr>
<tr>
<td>Chances of domino effect due to explosion is</td>
<td>(%) : 2</td>
</tr>
<tr>
<td>Domino effect due to missile</td>
<td></td>
</tr>
<tr>
<td>No chance of domino effect due to missile</td>
<td></td>
</tr>
<tr>
<td>Domino analysis : toxic release and dispersion</td>
<td></td>
</tr>
<tr>
<td>No analysis</td>
<td></td>
</tr>
</tbody>
</table>
Table 10. The result of DOMIFFECT for accident scenario 4

DOMIFFECT

R. J. Jan & S. A. Abbasi, Pondicherry-605 014, India

Result for scenario: Toxic release and dispersion with domino analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Event</strong></td>
<td></td>
</tr>
<tr>
<td>Toxic dispersion</td>
<td></td>
</tr>
<tr>
<td>Heavy Gas: Dispersion characteristics</td>
<td></td>
</tr>
<tr>
<td>Box Instantaneous: Model</td>
<td></td>
</tr>
<tr>
<td>Concentration at distance 200.00 (m), (kg/cu.m):</td>
<td>2.374443E-4</td>
</tr>
<tr>
<td>Puff characteristics:</td>
<td></td>
</tr>
<tr>
<td>Puff concentration at centre of cloud (kg/cu.m):</td>
<td>2.37443E-4</td>
</tr>
<tr>
<td>Concentration at cloud edges (kg/cu.m):</td>
<td>2.37443E-4</td>
</tr>
<tr>
<td>Distance along down wind (m):</td>
<td>259</td>
</tr>
<tr>
<td>Maximum distance traveled (m):</td>
<td>599</td>
</tr>
<tr>
<td><strong>Secondary event</strong></td>
<td></td>
</tr>
<tr>
<td>Domino checking</td>
<td></td>
</tr>
<tr>
<td>No hazard interaction, Go ahead!</td>
<td></td>
</tr>
</tbody>
</table>
### Table 11. Probabilities of different types of damages at different distances from the epicentre of the accident for scenario 3

<table>
<thead>
<tr>
<th>Damaging effect</th>
<th>at a distance of (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td>50% lethality by heat load</td>
<td>35%</td>
</tr>
<tr>
<td>50% injury due to shock load</td>
<td>65%</td>
</tr>
<tr>
<td>50% damage due to missile effect</td>
<td>--</td>
</tr>
<tr>
<td>50% lethality due to toxic load</td>
<td>--</td>
</tr>
</tbody>
</table>
Table 12. Probabilities of different types of damages at different distances from the epicentre of the accident for scenario 4

<table>
<thead>
<tr>
<th>Damaging effect</th>
<th>at a distance of (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td>50% lethality by heat load</td>
<td>--</td>
</tr>
<tr>
<td>50% injury due to shock load</td>
<td>--</td>
</tr>
<tr>
<td>50% damage due to missile effect</td>
<td>--</td>
</tr>
<tr>
<td>50% lethality due to toxic load</td>
<td>100%</td>
</tr>
</tbody>
</table>
the forecasts of scenario 2. Emergency preparedness plans should also be formulated keeping in view the worst possible impacts forecast by Scenario 2.

SUMMARY AND CONCLUSIONS

A new computer automated tool DOMIFFECT (DOMino eFFECT) has been described which can be used in studying the probabilities of occurrence and the likely impacts of 'chain of accidents' or 'domino / cascading' effects in chemical process industries.

DOMIFFECT enables one to know a) whether domino effects are likely to occur in a given setting, b) if they do what would be the likely accident scenarios, and c) what would be the likely impacts of the different scenarios. Finally, the tool guides us towards strategies needed to prevent domino effects.

The package has been coded in C++ and attempts have been made to give it the following attributes:

a) Wide applicability and sophistication - to this end DOMIFFECT has been studded with state-of-the-art models capable of handling a wide variety of accident situations with precision and accuracy;

b) user-friendliness - this has been enhanced by consciously making the packages easy-to-use and by incorporating adequate facilities for generating graphics;

c) flexibility - the modular structure of DOMIFFECT makes it easy to link it with other risk assessment tools; the package is also easy to 'add to' or 'revise'.

REFERENCES


