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TNO-report

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Analysis of the LPG incident in San Juan Ixhuatepec, Mexico City, 19 november 1984

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PREFACE

This analysis of the LPG disaster of 19 November 1984 in San Juan Ixhuatepec, Mexico City has been carried out by the Department of Industrial Safety of $TNO^{*)}$.

Relevant activities or knowledge in relation to this analysis are:

- * TNO maintains an incident data base (FACTS) for analysis of incidents with hazardous material (± 15,000 at this moment).
- * A great deal of experience and knowledge, especially on LPG-safety, has been built up in the past few years. TNO carried out an extensive safety study of the whole "integrated" Dutch LPG-system in that period. The study has been written down in a report [1]. Its main reports are available in English.
- * TNO developed the so-called "Yellow book": "Calculations of the physical effects of the escape of hazardous material" [2].
- * At the moment TNO is carrying out research on a (computer) model of how to act in emergency situations. The large amount of fatalities and injured people created special problems to the Mexican emergency services team. A check on reality.

In this incident analysis the experience and knowledge of the TNO Prins Maurits Laboratory on Explosion Effects and Damage has also been included.

Participation of the Dutch authorities

This study has been supported by three Dutch Ministries:

- Ministry of Home Affairs
- Ministry of Housing, Physical Planning and Environment
- Ministry of Social Affairs.

Ing. S.J. Paauwe from the Ministry of Home Affairs (Fire Inspectorate) joined the investigation team and contributed to this report with an analysis of the emergency handling at the time of the disaster.

*) TNO - the Netherlands Organization for Applied Scientific Research - is an independent, non-profit research and development organization.

Participation of Dutch Industry

In order to combine the available knowledge on incident analyses in the most efficient way and to broaden the basis of investigation, three safety experts from the Dutch Industry (operating large LPG storage facilities) joined the investigation team at the request of TNO. The experts in question also participated in the visit to Mexico City and in some technical discussions afterwards.

Visit to Mexico City early December 1984

The investigation team visited the disaster area about a fortnight after the disaster.

We wish to thank the Dutch embassy in Mexico-City for preparing our visit and arranging discussions with IMP (Instituto Mexicano del Petroleo), part of Pemex, the State Oil company that owns the plant in San Juan Ixhuatepec. IMP is responsible for the technical investigations concerning the disaster. The visit took about one week. Apart from the discussions with IMP, the team also interviewed the fire brigade, eye-witnesses of the disaster, members of the press etc.

Official information is available in a report of the Ministry of Health ("subsecretaria de Servicios de Salud"), 26.02.'85, written by Dr. H.F. Varela) and in two press bulletins of the Attorney General, dated 22.12.'84 (no. 488/84, see Appendix 1, and 26.12.'84 (no. 492/84).

Further information on which the analysis of this incident is based has been gathered from freely available material (press, discussions and interviews with the people involved) and observations by the team in the disaster area. The information given by IMP was limited; an official investigation, conducted by the Attorney General, was in progress at the time (and still is).

We thank the directors of IMP for their readiness to speak to us.

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Follow-up

More information will become available during the coming year(s). Some conclusions written down in in this report may also lead to further investigations and studies.

A sequel to the report will be issued when it is considered to be useful and will be made known to those who have acquired this report.



SUMMARY

In the early hours of Monday, 19 November 1984, one of the largest disasters in industrial history occurred.

In San Juan Ixhuatepec, Mexico City, a sequence of events at a large LPGstorage and distribution centre resulted in the destruction of the site and in about 500 fatalities and 7000 injured people in the nearby built-up area.

A TNO team with participation of Dutch industry and authorities visited the disaster area about a fortnight after the disaster, and spoke with Pemex, the State Oil company that owns the LPG centre.

This report presents the results of the analysis of the incident.

Some considerations about a possible start of the incident are given. However, the main purpose of the analysis was to check effect and damage models which are currently used in risk assessment studies. A major part of this report contains the results of this check. It is concluded that the calculated results of the models compare reasonably well with the actual damage in San Juan Ixhuatepec. However, the damage mechanisms in the case of BLEVEs of large amounts of LPG are not completely covered yet by the existing models.

A calculated maximum fatality distance (1% fatality is usually applied in risk assessment studies) gives a significant overestimation of the maximum fatality distance in San Juan Ixhuatepec. Mitigating factors should be taken into account.

An analysis of the fragmenting of the tanks leads to the conclusion that the positions of the cylindrical tanks were relevant with regard to the place where the fragments came down.

The lay-out of the storage site may have contributed to the fast development of the incident.

The large amount of fatalities and injured people is caused by the fact that the built-up area is situated close to the site and the very high population density in the area. This report also contains a description of the analysis of the emergency services during the disaster. It is confirmed that in this type of incident the emergency services have to face a very heavy task because of the rapid development of the incident.

Emergency services should be present at full capacity in a very short time. It is concluded that the emergency services in Mexico - which met the requirements to a great extent - were quite well organised.

The report further presents an overview of comparable incidents that occurred elsewhere and an extensive review of articles in Mexican newspapers from the days directly after the disaster. Photomaterial has been included.

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INTRODUCTION

Evaluation of effect /damage models

The primary purpose of this analysis is to check and evaluate the effect and damage models currently in use in risk assessment studies [1] or in risk assessment computer models. These models are mostly based on the "Yellow book" [2]. The following question is relevant in this respect: "How do the observed effect and damage distances and type of damage relate to the predictions of the models?"

The following models are in principle relevant to this disaster:

- outflow (source strength)
- heavy gas dispersion
- explosion models (overpressure/impulse distance relation):
 - . chemical explosion (vapour cloud explosion)
 - . physical explosion (bursting LPG storage tank)
- fragmenting (max. distances, mechanism, penetration capability)
- fireball dimensions/heat radiation
- vulnerability models for:
 - . heat radiation
 - . blast wave

Evaluation of the emergency services (fire brigade, medical service, etc)

A second purpose of this analysis is to study the performance of the emergency services shortly after the disaster; the fire brigade, the medical service, the police, the army, etc. The great intensity of the heat lasting many hours, the hundreds of dead and the thousands of severely injured people created enormous problems for these services.

Cause of the incident

It should be emphasized that an investigation into the cause of the incident was not a part of the scope of this analysis. However, every available piece of information in relation to a possible cause will be discussed in this report.

Design and lay-out of the installation

Possible lessons learnt from this disaster, concerning LPG installations (safety instrumentation, spacing, lay-out, etc.), are not included in this report.

By way of a follow-up, the safety situation with respect to large LPG storages will be reviewed in relation to the Mexican disaster. It is not possible to cover every aspect before more information on the installation in Mexico comes available.

Comparable incidents

Incidents comparable to the Mexican disaster will be described in this report. Eight "BLEVE"-type incidents involving large LPG storages are given. Another ten BLEVE incidents with transport (mainly rail) have been listed together with some relevant details as fragmenting, effect/damage distances, in relation to the Mexican disaster.

Press reviews/eye-witness reports

An Appendix with stories about the experiences of the people involved in this disaster is included in the report.

In order to be able to evaluate the effect/damage model, the investigation team composed a quite extensive press review from articles in mainly Mexican newspapers and magazines from the days immediately after the disaster. The team also spoke with several people who were actually in the disaster area at the time of the incident. A large number of eye-witness reports and photo material could be gathered in this way. The eye-witness reports have especially been given here for reference in relation to certain conclusions on the sequence of events or their effects, but also to complete the "image" of the disaster.

Available photo-, video- and press material

The large amount of press material (translated into English) is available for further research into other fields of interest such as reactions of the media, "truth" content of given facts, etc.

TNO may be requested to show the photo and video material and is prepared to present the material to companies, authorities, etc. together with the results of this analysis.

1. THE LPG STORAGE AND DISTRIBUTION CENTRE LOCATED IN SAN JUAN IXHUATEPEC, MEXICO CITY

1.1. San Juan Ixhuatepec

San Juan Ixhuatepec (also known as San Juanico) is one of the many northern suburbs of Mexico City. It is situated just beyond the borderline of Mexico City and the State of Mexico (see Figure 1.2.). San Juan Ixhuatepec numbers about 40,000 people, more than 100,000 if those who live in the hills are included. The hills surrounding the village are: Zocatenco (south), Chiquihuite (west) and Cuanahuatepec (north). The majority of the inhabitants of San Juan Ixhuatepec are country people who went to Mexico City in hope of a brighter future.

In Figure 1.2. it is shown that the suburbs have developed during the past 20 years. There were no buildings present at the time when the construction activities of the LPG-facilities started. The built-up area of San Juan Ixhuatepec, which was mostly affected by the disaster, is situated south of the LPG-facilities and with its borders at a distance of about 130 meters from the storage tanks (see Figure 1.3.).

The majority of the houses in San Juan Ixhuatepec is of the same built: walls constructed of concrete pillars filled in with bricks. The roofs are made of concrete, but very often also of iron sheets. There are also a number of one-storeyed houses made of concrete. Furthermore there are a few more plain houses, chiefly situated along the northern side of the railway, east of the LPG-facilities (see Figure 1.3.). These houses have basically been constructed from wood and iron sheets.

1.2. The LPG-facilities before the disaster

The lay-out of the LPG-facilities as they were in San Juan Ixhuatepec is given in Figure 1.4. The facilities are owned by the Pemex State Oil Company and functioned as an LPG bulk storage and distribution depot. It consisted of 6 spherical storage tanks (4 with a volume of 1600 m³ and 2 with a volume of 2400 m³). The facilities comprises an additional 48 horizontal cylindrical bullet tanks of different sizes (see Figure 1.4.). The overall storage capacity was about 16,000 m³, for mainly propane and LPG (a mixture of propane and butane). The tanks contained propane and high and low volatility LPG.

At the time of the disaster the storage tanks together contained about 11,000 m^3 .

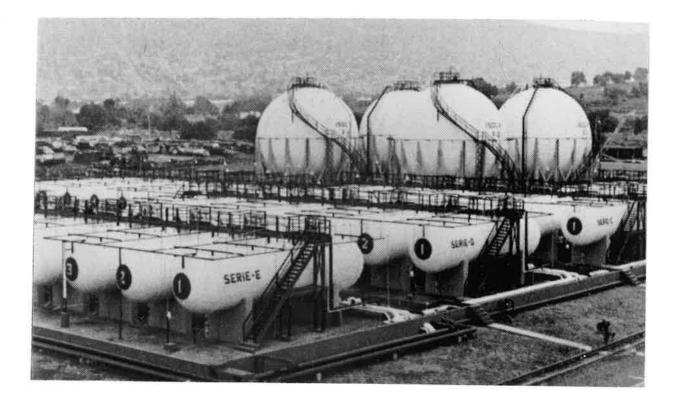
The storage and distribution centre was fed by three underground pipelines. A 12" line came in from Minatlan over a distance of 576 km. The capacity of this line was about 10,000 m³/day, of which 50% was pumped through to Tula (at a distance of \pm 80 km). A 4" line came in from Poza Rica over a distance of 235 km (capacity: 800 m³/day) and a 4" line came in from the refinery at Azcapotzalco (over a distance of 8 km, also with a capacity of 800 m³/day). The LPG was distributed to the two adjacent privately owned distribution companies (Unigas and Gasomatico) through underground pipelines. Further away from this site, another 5 gas distribution companies took gas from the distribution centre using tank trucks and bottles. The Pemex site therefore accomodated a tank truck filling station, a gas bottling plant and a rail tankcar filling station.

The storage and distribution centre in San Juan Ixhuatepec was built around 1962. The two largest spherical storage tanks were constructed in 1981 (see Figure 1.2.). A picture of a part of the facilities is given below. The two largest spheres had not yet been constructed at the time when the picture was taken (about 1979).

The site further accomodated two flare pits, a fire protection system complete with pond, pumps and waterspray distribution. More detailed information, e.g. in the form of engineering diagrams, was not available at the time when this report was issued.

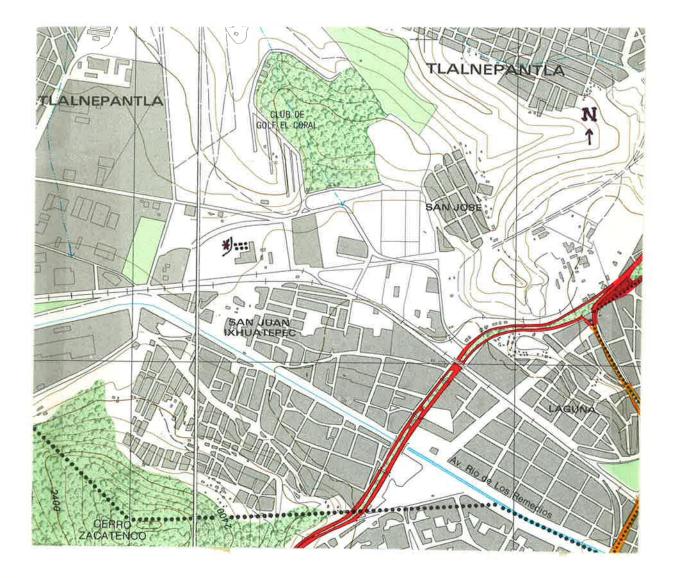
According to information from Pemex-IMP, the larger spheres had a relief valve set pressure of 150 psig and a wall thickness of 37 mm.

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The installation about 1979 (photo from Pipeline and Gas Journal, October 1979)

The remains of one of the smaller cylindrical vessels had a measured wall thickness of 28 mm (measured by the team). It was also noticed by the team that the legs of the two remaining spheres were apparently not fire-proofed. The same applies to the four smaller spheres (see photo). The picture shows product lines, fire water lines and vapour blow-off lines to the flare pits. Although it is not quite clear from this picture, from other sources, among which a video tape of the facilities on fire, it may be concluded that separate fire relief valves were installed on each tank. The bund walls with a height of about 1 m are shown. The separate bunds are indicated in Figure 1.5. The bunds divided the storage area into 13 separate areas. The cylindrical tanks were numbered in series and the spheres were numbered F-1/F-6 (Figure 1.5).



*) Pemex LPG facilities Scale 1:20,000 Borderline Mexico City / State of Mexico (north of the line)

Figure 1.1. San Juan Ixhuatepec, State of Mexico.







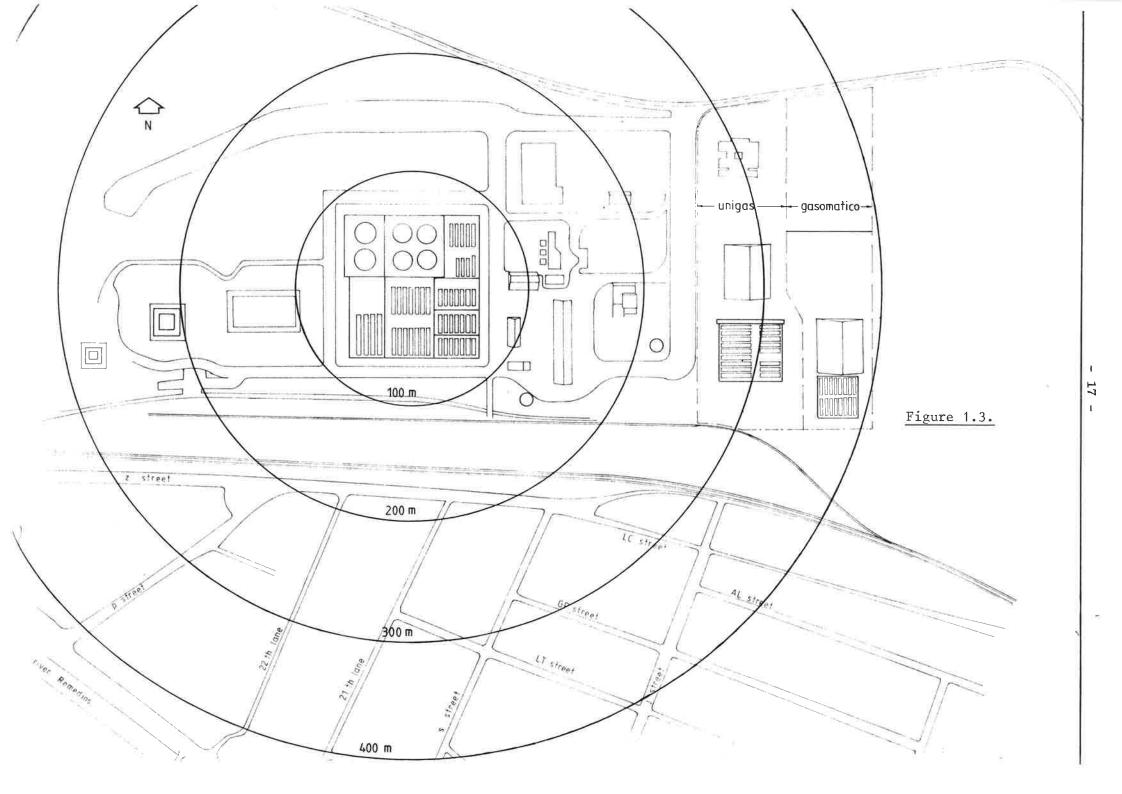


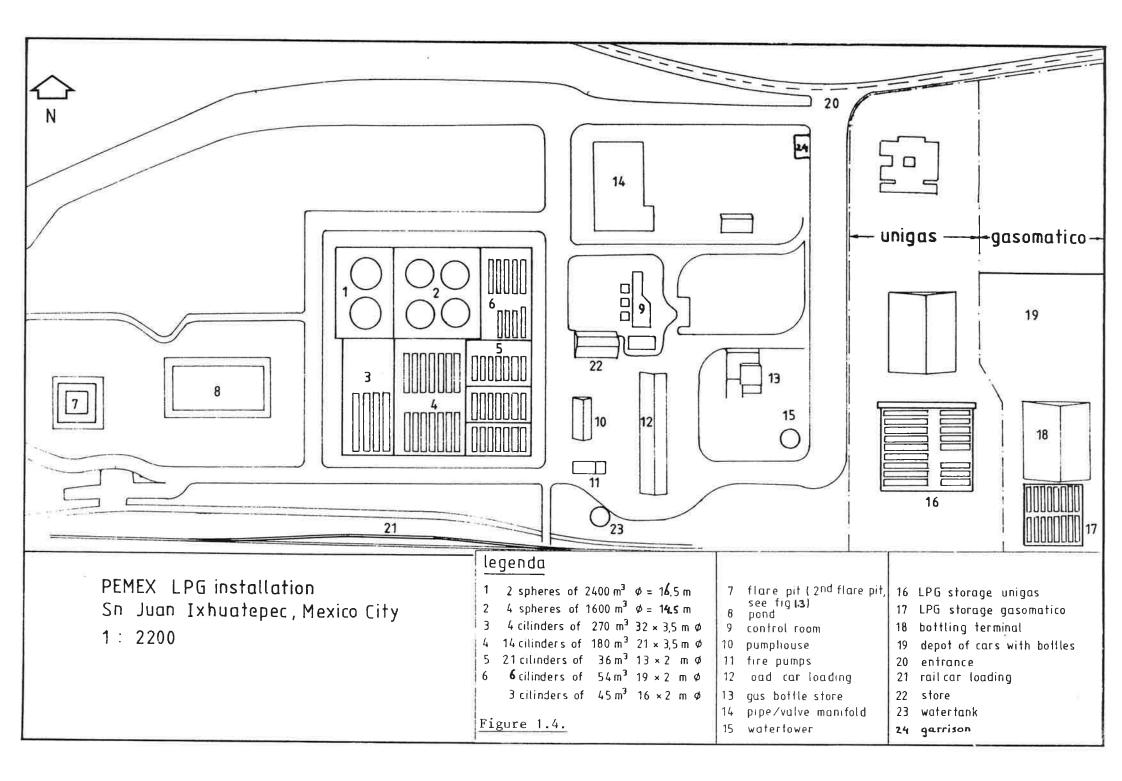


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Figure 1.2. Growth of the installation and built-up area.

*) cylinders





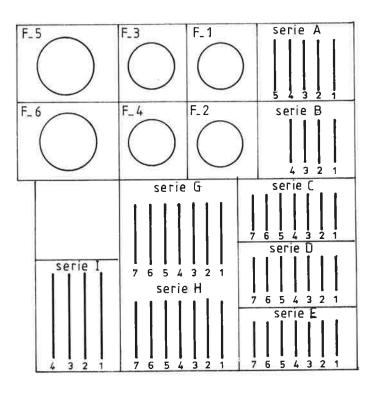


Fig. 1.5. Storage tanks identification

2. THE DISASTER AND SUSTAINED DAMAGE

2.1. The disaster

In the early hours (± 5.45 a.m.) of Monday, 19 November 1984, a sequence of events at the LPG-facilities in San Juan Ixhuatepec, Mexico City (described in Chapter 1) led to one of the greatest disasters caused by industrial activities. An extensive fire and a series of violent explosions resulted in an almost complete destruction of the storage facility. The sequence of violent explosions was registered by the University of Mexico, situated at about 25 km from San Juan Ixhuatepec. The timing of the various explosions, according to the seismographic recordings, is given in table 2.1. The final registered explosion occurred at about 7 a.m. Smaller explosions continued until 11 a.m. and the fire lasted until 8 p.m. At the plant, 5 workers were killed and 2 suffered severe burns. Outside, in the built-up area which is mainly situated south of the facilities, approximately 500 people were killed and approximately another 7000 were injured. The work of the emergency services, which started immediately, is described in Chapter 4.

Over 200,000 people were evacuated in a period of 12-14 hours. The majority of the dead were found in the built-up area within a distance of 300 meters from the centre of the storage area.

2.2. The damage at the storage facility (see photo 3)

The storage tank area was completely destroyed in the events. Four smaller spheres (F1-F4, figure 1.5.) completely fragmented and vanished altogether. A great number of fragments were scattered all over the place; most heavy fragments are marked in the figures 3.2. and 3.3. The largest spheres (F5/F6) remained intact. However, their legs were weakened, causing the spheres to tilt toward the ground. At least one of them ruptured at the top.

From the cylindrical bullet tanks the series I was the relatively most unaffected one. The tanks I4, I3 and G7, G6 were the only ones that were not blown off their supports. Parts of the series I tanks were still covered with paint. Of the series G, 5 tanks were pushed off their supports, but shifted only a few meters and they were probably still arranged in their original order. They were apparently shifted by a blast wave from an explosion of one or more of the series H cylinders. Three cylinders from this series disintegrated completely. Two of them were shifted by the (same ?) blast wave into the bund of series I. The smaller tanks were scattered all over the place, some over considerable distances into the built-up area (figure 3.1.). An analysis of the fragmenting and propelling aspects has been made in Chapter 3.2.3. From a total of 48 cylinders, a number were found at the site; 12 cylinders had flown over considerable distances (figure 3.1.) and the rest (4) had disintegrated.

Except for the storage area, the damage to the facilities at the Pemex plant was limited to local fires of buildings (see photos 3 and 11). At the adjacent Unigas site the main office was partly destroyed by a fragment. At the time of the team's visit almost all 17 storage tanks were covered with white paint. From photographs it can be seen that there was a flame on one of the relief valves at the time of the disaster. The storage tanks at the Gasomatico site remained unaffected. These tanks were apparently well cooled at the time of the disaster. However, at the Gasomatico site, a large car-park containing almost 100 trucks loaded with LPG household cylinders (20-40 kg) was completely burned-out. There were hundreds of explosions. This fire is assumed to have been started by a fragment from the Pemex site, because no damage was found at the Unigas site (see also Chapter 2.4.). At the Gasomatico site a two-storeyed building was also damaged.

2.3. The damage in the built-up area

The damage in the built-up area was heavy and dramatic. Approximately 500 people were killed and approximately 7000 were severely injured by the fire. The majority of the people killed or injured were still asleep in their homes when they were surprised by the fire. A number were caught as they tried to escape. More accurate data on the locations of the killed and injured at the time of the disaster will become available when the official reports are issued. TNO will continue to try and obtain additional information.

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The Mexican authorities divided the damaged area into a "partly affected" and an "affected" area. The houses were marked accordingly PA and A. At the time of our visit, most houses marked A had already removed (a fortnight after the disaster). However, from our own observations, aerial photographs taken directly after the disaster, locating specific spots from video shots and photos (see Appendix 8), and from interviews with people living in San Juan Ixhuatepec, the heavily damaged area has been identified and is shown in figure 3.2. This area lies within a distance of about 300 meters from the site.

Here, "heavily damaged" is defined as "completely destroyed" or "destroyed to a major extent" (collapsed roofs, blown out walls, etc.). This is almost similar to the Mexican definition: "affected". The cause of the damage will be described in the following chapters. Photographs (Appendix 8) show that damage from overpressures (blast waves) is relatively low. The major part of the damage can be concluded to have been caused by intense fire and heat radiation lasting several hours, and may be due to occasional explosions inside the houses.

Plain wooden houses were burned down at distances up to 500 meters. Additional local damage was caused by the fragmenting and propelling of storage tanks. Several houses were destroyed at distances of up to a maximum of 1200 meters. The team failed to observe glass damage. However, two cases of broken window-panes are now known: both at a distance of about 600 meters and facing the fire. It is thought that this particular damage was mainly due to the heat radiation (photo 23, Appendix 8).

2.4 Possible development of the incident

Uncertainties exist about what started off the accident, although it is certain that an outflow of LPG occurred. This could have been caused by different reasons (given the available information):

- a pipe leakage/rupture
- a relief valve of an overfilled vessel
- unburned gases from the flare

Pipe leakage in the area of the cylindrical tanks has been reported in the official report of the Attorney General (Appendix 1) and in the press by a Unigas official.

A description of the start of the disaster, given to the TNO team by a member of an official investigation team of the army, confirms the LPG leakage in the section with cylindrical tanks: military guards (who survived the disaster in the garrison, see figure 1.4. no. 24) saw the LPG flowing over the walls of about 1 m height which surround the tanks. They tried to remove several people from the threatened area before ignition. The vapour cloud had a visible height of about 2 meters when ignition followed. The vapour cloud was probably ignited by a flame at the gas bottling store. A number of people describes the visible part of the vapour cloud as several separate clouds; upon ignition several explosions were heard.

More evidence for a vapour cloud is the smell of gas prior to the disaster that has been mentioned several times. Also fire in the streets in combination with the first, relatively small, explosion, and prior to the second heavy explosion (5.46'.01", see table 2.1.) points to a vapour cloud (ignition). The ignition at the plant site, is confirmed by evidence (press) of flame fronts leaping from the plant through the surroundings. The bulletin of the Attorney General (Appendix 1) also mentions a burner on the Pemex site as the ignition source. This open flame was probably located at the top of the gas bottling store.

From an analysis of various reports in the press (see Appendix 4), it may be concluded that ignition of the vapour cloud was followed by an extensive fire at the plant area.

It is assumed that the vapour cloud explosion was the first registered explosion by the University of Mexico (table 2.1.). No evidence was found of a fire of specific duration (more than a few minutes) prior to the first explosion (5.44'52" on the seismograph, see table 2.1.). After 1 minute and 9 seconds the second, very heavy explosion occurred (see seismic readings and press). This allows for only a very short time in which a fire may could have developed a BLEVE of one or more storage tanks. This period of time is very short but from calculations it

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follows that it is possible to generate a BLEVE in this period of time in "impingement" situations of a vapour space.

The incident in Texas (1978, see Chapter 5) reported a BLEVE of an LPGsphere within 5 minutes after ignition, and in Port Newark (1970) a fireball was reported 3 minutes after ignition (see Chapter 5). However, in the case of the LPG incident at the camping Los Alfaques (Spain, 1978), a BLEVE occurred one minute after ignition [14]. The report in question states: "Thus it is a strong possibility that a gas cloud formed from a partial leak of cargo and after a short time found a source of ignition and flashed back to the leaking tanker. Because the tanker was weakened, due to overfilling (and possibly some stress corrosion), the engulfing fire caused a BLEVE in a time much shorter than would have been the case for a vessel in sound condition".

This scenario certainly applies to the already mentioned evidence at San Juan Ixhuatepec. Some versions from different sources fit in as well. For instance, problems with the instrumentation (level instrumentation) due to high sulfur content of the LPG were mentioned.

Although a number of uncertainties still exist, a combination of information from several independent sources and the given development of the incident lead to a prudent assumption that the LPG leak may have been caused by an overpressure of one or more pipelines and/or cylindrical vessels, in combination with overfill. The high pressure may have been caused by the high discharge pressure (> 60 bar) of a boosterpump in one of the underground pipelines.

The second and heaviest explosion at San Juan Ixhuatepec, probably destroyed quite a number of houses. It was reported to have been an earthquake. Several papers mentioned that two cylinders were launched several hundreds of meters away in this explosion. However, from eye-witness reports, gathered by the TNO team, it can be stated that this is very unlikely. The "propelling" effect of the cylinders started only later. Information from the fire brigade makes it clear that by the time they arrived two of the smaller spheres had disappeared. Presumably this is what happened at the second explosion. The connecting BLEVE caused tongues of fire large enough to reach the built-up area. Table 2.1. Times of disturbances, registered by the seismograph of the University of Mexico, on 19 November 1984.

1.	5h	44 min.	52 sec.
2.	5h	46 min.	01 sec.
3.	6h	15 min.	53 sec.
4.	6h	31 min.	59 sec.
5.	6h	47 min.	56 sec.
6.	6h	49 min.	38 sec.
7.	6h	54 min.	29 sec.
8.	6h	59 min.	22 sec.
9.	7h	01 min.	27 sec.

Disturbances number 2 and 7 were the most intense. Both had, according to the Seismic Service of the University of Mexico, an intensity of 0.5 on the scale of Richter.

Conclusions

There is strong evidence that an LPG vapour cloud had formed prior to the first explosion. The LPG was in all probability released from a leaking cylinder or pipeline in the cylindrical tank area. Overfill of a vessel, in combination with overpressuring by a pipeline boosterpump (discharge pressure > 60 bar), probably played a part. The ignition of the vapour cloud took place at the Pemex site and did not result in significant effects of overpressure in the built-up area. It started several fires and some houses may have been destroyed due to explosions of the gas that had accumulated in the houses.

The ignition of the vapour cloud may also have damaged some of the piping at the site of the plant, due to the large degree of confinement in the storage area. This could account for the extensive fire immediately after the ignition.

Approximately one minute after ignition of the vapour cloud one of the heaviest explosions of the whole sequence occurred. Impingement of a vessel weakened by overfill and overpressuring may account for such a short time. Some eye-witness reports mentioned that this particular explosion was followed by an "earthquake" which destroyed houses. Again, from interviews, this explosion (BLEVE of one or, more likely, two of the smaller spheres) had the most disastrous effect. Unburned and burning gas entered the houses and set fire to everything. A blast wave of the physical explosion not only destroyed a number of houses but also shifted several cylindrical tanks from their supports, adding more gas to the fire. More cylinders exploded (BLEVE-ed) during the next 68 minutes (4 BLEVEs were registered on the seismograph, see table 2.1.). At 6.54'.29" another extremely violent explosion comparable to the second one occurred. It is assumed here that once more two smaller spheres BLEVE-ed (the 68 minutes agree with the cases described in chapter 6). Two subsequent explosions were registered (table 2.1.).

Further analysis, chiefly of the effects of explosions and fragmenting, is given in chapter 3.

The following aspects will be discussed in chapter 3:

- 1. Overpressure effects of an unconfined vapour cloud explosion.
- 2. The minimal time necessary to initiate a BLEVE in case of flame impingement.
- 3. Overpressure/impulse effects of the physical explosions (BLEVEs).
- 4. Penetration capability of fragments (domino effects).
- 5. Fragmenting of the tanks, range prediction.
- 6. Heat radiation/fire effects of a BLEVE.

3. CALCULATION OF EFFECTS AND DAMAGE USING EXISTING THEORETICAL MODELS AND COMPARISON WITH ACTUAL REPORTED DAMAGE

For the analysis of the damage involved in this disaster, two scenarios are basically relevant:

- 1. a vapour cloud explosion
- 2 a BLEVE (rupture of the vessel, see 3.2.)

The mechanisms responsible for the damage are blast waves and fire and/or heat radiation.

For both scenarios the possible (theoretical) damage to the surroundings will be assessed and compared to the actual situation in San Juan Ixhuatepec.

3.1. The effects of a vapour cloud explosion

As has been described in Chapter 2, there is strong evidence that a vapour cloud developed prior to ignition of the escaped gas. LPG-gas is heavier than air and will spread out and disperse in the atmosphere along the ground, influenced by weather conditions, wind speed, obstacles, etc. A calculation of the size of the explosive part of this vapour cloud is carried out in the case of an outflow of LPG from a ruptured pipe with a diameter of 4" (the typical size of a pipeline connection to an LPG-cylinder). The calculation leads to a maximum distance of the front of the explosive (flammable) cloud from the point of release of at least 200 m. This, in the case of weather conditions comparable to the situation at the time of the disaster (7°C, hardly any wind).

The damage resulting from the ignition of a vapour cloud can be divided into two parts. First, damage by fire to people and material inside the cloud. According to an analysis of about 165 vapour cloud explosions [4], people inside such a cloud have a small chance of surviving the fire. Some material in the cloud may catch fire, but the flame front passes very quickly. Some secondary fires to buildings may develop, but it can be stated in general that a substantial part of the houses inside the burning vapour cloud will not be destroyed by the fire [4]. A second mechanism for damage resulting from the ignition of a vapour cloud, is the effect of overpressure. This effect may occur only in confined or semi-confined situations. The flame front velocity will be enhanced in such a way that a blast wave develops. The higher the flame speed, the higher the level of overpressure inside the blast wave will become and more damage will be caused in principle. In the past, models have been developed in order to quantify these effects. Nevertheless their reliability is questionable. Therefore, this report follows an alternative route: A check-up with the results of analysis of accidents and experiments [4,5] has been made. Some results of the analysis of 165 vapour cloud explosions are given in Appendix 2.

Comparison with the actual damage in San Juan Ixhuatepec:

The distance from the storage area to the far border of the area where most of the houses were destroyed was about 300 m. Hardly any blast wave damage beyond this distance was noticed by the investigation team.

The following can be stated about the effects of the vapour cloud explosion in the built-up area:

* From incidents and calculation models it can be concluded that effects of overpressure caused by a vapour cloud explosion in the semi-confined built-up area in San Juan Ixhuatepec could have severely damaged the houses (see also 3.2.1.). Explosions inside the houses will almost certainly have destroyed them. From eye-witness reports however, it may be concluded that the vapour cloud explosion was not responsible for the major part of the damage to the houses. It has been quite often stated that the second explosion (BLEVE) had the most violent nature and destroyed the houses (see also 3.2.). From photo material it can be concluded that there was indeed only minor blast wave damage in the area (Photo 11). The greatest damage was probably sustained from explosions of the

gas that had accumulated inside the houses (photos: 15, 18), and from fire and pressure effects from BLEVEs (see 3.2.). The photos are given in Appendix 8.

- * Damage by fire from the burning vapour cloud (flash fire) probably only occurred on a small scale. People in the streets within a radius of 200-300 m probably did not survive because of direct flame contact, the heat and lack of air. Eye-witness reports from people who were beyond this distance and who survived the flash fire are given in Appendix 4.
- Based on experiments [5] and theoretical considerations, it is unlikely that the impulse - generated by the vapour cloud explosion

 on cylindrical and spherical vessels will be large enough to throw the vessels off their supports. However, the impulse might contribute to leakages, by moving the cylinders on their supports. This is possible because of the close lay-out of the cylindrical vessel area.

Conclusions concerning the vapour cloud explosion damage

Built-up area:

- The vapour cloud explosion in San Juan Ixhuatepec possibly damaged a few houses within a maximum range of about 300 m from the LPGstorage location. It is basically true that hardly any blast wave damage was sustained. Unsupported, fragile walls (photo 11) were left undamaged to a great extent. However, a number of houses may have been destroyed by explosions from inside.
- The flash fire may have started some local fires and people were killed by the heat and lack of air.

However, the vapour cloud explosion is unlikely to have determined the extent of the damage to the built-up area. The BLEVEs and especially the one that occurred just one minute after ignition of the vapour cloud had much greater effect (see 3.2.).

LPG-storage area:

The vapour cloud explosion probably generated sufficient pressure to cause more leaks in the area where the cylindrical storage tanks were positioned, due to its close lay-out.

3.2. Description of the effects of a BLEVE

The acronym "BLEVE" stands for Boiling Liquid Expanding Vapour Explosion. It is a type of explosion that occurs upon rupture of a vessel containing a liquid with a vapour pressure well above atmospheric pressure.

However, the acronym BLEVE is generally specifically reserved for a rupture of a vessel containing a liquefied flammable gas (under pressure) in case of fire. Such a rupture can be initiated by several mechanisms (or a combination of mechanisms):

- overpressure of the vessel due to overfilling, a too small relief
 valve and high pipeline pressures;
- heating of the vapour space of the vessel by a great fire or a flame on a specific spot ("flame impingement"). Although the relief valve may function according to its set pressure, the tank ruptures because of the weakening of steel. This type of BLEVE may occur quite soon (within minutes) after the initiation of the fire.
- heating of the (internally) wetted surface of the vessel through a fire underneath. A rupture may occur in the case of a malfunctioning relief valve. Alternatively, the heating may finally lead to the above mentioned mechanism, when part of the liquid has vaporized and is blown off through the relief valve, increasing the size of the vapour space. In these cases it may take hours to initiate a BLEVE;
- A rupture of the vessel may also occur when it is for example penetrated by missiles originating from a BLEVE of a nearby vessel.

A BLEVE of a vessel containing LPG can have disastrous effects within a specific distance from the ruptured vessel.

The effects of a BLEVE of a vessel containing LPG are listed below:

- 1. Blast wave effects due to the physical explosion:
 - . expansion of the gas above the liquid,
 - . flash evaporation of the liquid.
- 2. A fireball will result if the escaped material is ignited.

3. The ductile tank tears and a relatively small number of fragments are produced. The fragments may be scattered over considerable distances by the energy that is released by the gas expansion.

3.2.1. Blast effects from physical explosions

A substantial amount of research has been carried out in determining the blast wave produced by bursting pressurized vessels (containing gas and/or liquid).

References [3], [6] and [7] indicate that for vessels containing gas and liquid, the vapour space determines the size of the blast wave. The flash evaporation from the bulk fluid is a relatively slow process that produces a small degree of overpressure at relatively low temperatures, (compared to the atmospheric boiling point). The effects of overpressure from this evaporation will increase with the rise in temperature of the liquid. It is stated in [3] that for propane the minimum temperature at which the flash evaporation becomes dominant is about 55°C. It takes a long time to heat the contents of the LPG-vessels to this point, and it had certainly not been reached at the time of the second and heaviest explosion shortly after the disaster was initiated in San Juan Ixhuatepec.

It is necessary to calculate the peak overpressure and the specific impulse of the blast wave in order to be able to predict the damage caused by a blast wave. These parameters are diminishing functions of distance from the centre of the blast wave.

Calculated overpressure/distance relations (see Appendix 5) are given here, both for models used in [3] and in the "Yellow book" [2]. These relations have been compared to the actual damage sustained in San Juan Ixhuatepec. Moreover, specific impulse calculations have been done according to [3], in order to check the possibility that the blast wave from a BLEVE may actually throw vessels off their supports (as happened), or cause the overturn of (tank)cars at a specific distance (tank cars close to the site did not overturn).

3.2.1.1. Vapour expansion model

(see table 3.1.)

		Vapour	space volu	ume (m ³)		
	20	10	0	800	1	200
Distance (m)	[3]	[2]	[3]	[3]	[2]	[3]
10	0.44	0.7	1.0	2.3	2,0	2.6
50	0,04	0.08	0.08	0.23	0.2	0.29
100	0.018	0.030	0.033	0.09	0.09	0.10
200	0.0075	0.015	0,012	0.033	0.04	0.04

Table 3.1. Peak overpressure (bar) as a function of distance according to [2] and [3] for an LPG-vessel (bursting pressure 13.4^{*}) bar).

*)Set pressure of the relief valve (reported by Pemex) + 20%.

Conclusion

The models given in [2] and [3] are well comparable. It is shown that at distances twice as large, the overpressure decreases with approximately the same factor (for greater distances).

Before the actual damage is compared to the calculated overpressures, the overpressures resulting from adiabatic flash evaporation, are calculated.

3 2.1.2. Adiabatic flash evaporation

Calculations of blast wave effect/distance relations have been carried out with the model given in [2]. The results are given below (table 3.2.) and have been calculated for 50% filled storage tanks. The bursting pressure has once more been set at 13.4 bar. The boiling point of propane at this pressure is about 40°C (superheat 80°C).

Table 3 2. Overpressure/distance relations based on adiabatic flash evaporation of the liquid LPG, calculated for bursting of different sizes of storage vessels at San Juan Ixhuatepec (50% filled).

Superheat temperatures			overpressure (bar)				
80 K		3	1	0.3	0.1	0.03	0.01
50 K		2	0.6	0.15	0.05	0,015	0.003
Tankcapacity (m^3) Liquid content (m^3)			distances (m)				
2400	1200	30	64	140	300	640	1100
1600	800	26	56	120	260	560	940
270	135	15	31	68	150	310	520
180	90	13	27	58	130	270	450
54	27	8.5	18	39	85	180	300
45	23	8.0	17	36	80	170	280
36	18	7.3	16	34	73	160	260

Table 3.3. Overpressure/distance relations for different blast wave models, given a bursting vessel (50% filled).

Vessel volume (m ³)	2400		1600		20	00
Vapour space (m ³)	1200 800		10	00		
	1)	2)	1)	2)	1)	2)
Distances for	30	10	140	50	27	10
the same	140	50	300	100	270	100
overpressures (m)	300	100	560	200	450	200

1) Distances calculated using the adiabatic flash evaporation model [2].

2) Distances calculated using the vapour expansion model [3], see also table 3.1.

Conclusions from table 3.3.

The flash evaporation model using saturation temperatures at bursting pressure produces distances three times as great as the vapour expansion model.

Remarks:

IIn case of a liquid LPG temperature of about 10-15°C, the distances with the flash evaporation model are about 1.5 times as great as the calculated distances using the vapour expansion model. For the completely filled vessel the distances 1) in table 3.3. are $\sqrt[3]{2} = 1.26$ times as great as those given.

3.2.1.3. The shifting of the cylindrical vessels

A number of cylindrical vessels were blown off their supports. Several were scattered over distances ranging from a few to up to 1200 meters. Two mechanisms may be reponsible for the shifting:

- 1. A blast wave from an explosion of a nearby vessel.
- 2. A counter-pressure from the LPG released from the ruptured vessel or from a pipeline connected to the vessel.

ad 1:

Calculations using the method in [3] give the overpressures and specific impulses determined by a blast wave of a ruptured vessel. This blast wave mainly originates from the vapour expansion of the LPG vapour space. It follows from this calculation that vessels at a distance of 10 meters from the exploding vessel will only be shifted if the vapour space volume of the exploding vessel is greater than a few hundred cubic meters. In the case of vessels at distances of a few meters (a neighbouring vessel) a vapour space volume of about 100 m³ is sufficient. However, due to the small side dimensions of the cylindrical tanks, "dragloading" [3] becomes an important factor. This is the load caused by the resistance of the tank to an air-flow which comes with a blast wave [3]:

$$\bar{Q} = C_D \cdot \frac{5}{2} \cdot \frac{\bar{p}^2}{7+\bar{P}_s}$$
 \bar{P}_s : overpressure
 $C_D : drag coefficient (cylinder: 1.2)$

To shift a vessel, a load of about $\overline{Q} = 0.1$ bar is required, which means an overpressure of about 0.18 bar. Given the overpressures calculated in Chapter 3.2., a shifting of the cylinders which actually took place can be accounted for with a "dragload". Blowing the vessels over larger distances, due to the dragload, can be excluded with the calculated overpressures and the estimated duration of the load of 20 ms.

<u>Ad 2:</u>

The counter-pressure of the outflowing LPG determines the effect. The fact remains that the burning LPG hardly contributes: the flame is at a certain distance from the hole; close to the hole there is a lack of oxygen. Depending on the forces acting on the cylinder, the size of the hole and a possible lift, the distance of the shifting can range from a few meters to several hundreds of meters. In this particular incident, an exeptional distance of 1200 m was reached.

Comparison with the actual damage in San Juan Ixhuatepec

The maximum distance within which substantial damage to the houses in the built-up area at the southern part of the Pemex site occurred is about 300 m for the houses built of stone and concrete, as has been described in Chapter 2.

(Wooden houses were destroyed by fire at distances of over 400 m). Local damage, caused by fragmenting, has been found up to a maximum distance of 1200 m (see 3.2.3.). Hardly any substantial glass damage has been found beyond a distance of 300 m. However, glass damage at over 500 m did occur on at least two spots (see photo 23). The windows in question were directly facing the fire and may have been broken as a result of the heat (see 3.2.2.).

Vulnerability models have been developed for the assessment of damage to constructions under blast wave conditions [8]. Such models normally use simple overpressure criteria. No distinctions can be made between pressure/time relations, duration of the pressure load and reflections. In [8] and [4] an overpressure of about 0.1 bar has been taken to be the limit beyound which structural damage to "houses" may occur. The resistance of houses to blast waves varies, depending on structure, height, material etc. The simple type of houses in San Juan Ixhuatepec's built-up area will probably already collapse at overpressures well below 0.1 bar^{*)}. In literature [9], values of 0.01-0.04 bar are used as limits for glass damage.

Given the above-mentioned limits, it follows from table 3.2. that damage to glass may be expected at distances far beyond 300 m. Structural damage up to distances over 300 m is possible. However, such blast wave damage has not been discovered by the investigation team, neither from their own observations, nor from press reviews or eye-witness reports. The flash evaporation model is concluded to give an overestimation of effect and damage distances in the case of this incident. The distances given in table 3.1. (vapour expansion model) are smaller than the above-mentioned damage distances. However, it cannot be concluded that this model underestimates the distances, because other mechanisms may have damaged the houses up to 300 meters.

3 2.2. The fire and heat radiation damage

The many fires and highly intense heat radiation contributed for a major part to the damage to the built-up area and was responsible for the fact that about 500 people died and thousands were severely injured. Fires in the streets were probably caused by unburned LPG spilling into the area. The highly intense heat radiation was caused by "fireballs" produced by the BLEVEs of the vessels, a process which lasted about an hour and a half, and the extensive fires at the storage area which lasted for several hours more. The continuous fire was fed by ruptured vessels and pipes. Probably one or more of the three underground pipelines feeding the facility with LPG (12", 4" and 4", see Chapter 1) also contributed to the fire.

Some photographs and video material point in that direction. From photos 27 and 28 (Appendix 8) and looking at a map it may be concluded that at the time photo 27 was taken, the pipeline manifold was on fire (see also "other fires" in this chapter).

*) In [8] a limit is given of 0.03 bar for severe damage to a warehouse (steel structure filled in with bricks).

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The pipeline manifold at the site itself seemed undamaged and even the paint did not seem affected. However, repainting activities at the time of the visit of the team was going on.

Theoretical models for the BLEVE fireball

A BLEVE generally produces a fireball upon ignition. The existing models giving fireball dimensions (diameter) and fireball durations are mainly based on small-scale experiments. A comparison between six different empirical models is given in [1]; there is no substantial difference. The model used in [1] is an average value of the six in question and is given below (see also [3]):

diameter of fireball:	$D = 6,48 W^{0,325} (m)$	(1)
duration of fireball:	t = 0,852 W ^{0,26} (sec)	(2)
W = amount of flammable	material in the fireball (kg).	

In [1] a comparison of the calculation results with the above-given formulae and the estimated fireball dimensions and duration has been carried out. The results are given in table 3.4.

Table 3.4. Dimensions	(diameter)	and	duration	of	fireballs	in	accidents.
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2		Repo:	rted	Calo	culated
Place and date of accident	Amount (kg)	D (m)	t (s)	D (m) (1)	t (s) (2)
Celle, Germany 1958.01.03	2.7 10 ⁴	D=50-100		180	12
Crescent, Ill. 1970.06.21	6.4 10 ⁴	D=200	-	240	15
Houston, Texas 1971.10.19	16.5 10 ⁴	300	-	320	20
Kingman, Arizona 1973.07.05	1.6 10 ⁴	D=240	-	210	14
Nijmegen, Holland 1978.12.18	1.5 10 ⁴	D= 40	secs	150	10
Lynchburg, Virg. 1972.03.09	1.8 10 ⁴	240	-	160	11

Calculation results for maximum fireball diameters and duration in the case of the LPG storage vessels in San Juan Ixhuatepec are given below. It is assumed that the vessels were filled to 90% and that the complete content was burned in the fireball.

Vessel volumes (m³)	W (10 ³ kg)	Diameter fireball (m)	Duration fireball (sec)
1600	735	520	29
270	125	300	18
180	83	260	16
55	25	170	12
45	20	160	11
35	16	150	11

Table 3.5. Calculated fireball dimensions for 90% filled vessels in San Juan Ixhuatepec.

Actual fireball dimensions in San Juan Ixhuatepec

The actual sizes and durations of the fireballs in San Juan Ixhuatepec are difficult to estimate. From photos and video material (see photo 1, Appendix 8) it can be estimated that there were diameters of about 200-300 meters, and durations of approximately 20 seconds have actually been registered on video.

The direct damage from fire in the area however, includes distances up to about 300 meters. Yet, if this damage was caused by a fireball, the diameter should have been 600 meters.

However, the fireball from the second explosion, registered on the seismograph, was not photographed or registered on video.

Heavy damage at a distance of up to 300 meters can be concluded to agree reasonably well with the calculated maximum radius of a fireball that may have occurred.

As is customary in risk assessment studies, the radius of the fireball is taken to be the maximum distance for heavy damage; and people within the projection of the fireball will not survive. In the case of the disaster in San Juan Ixhuatepec this approach would have predicted the distance for heavy damage reasonably well, given the BLEVE of a sphere of 1600 m³, and the assumption that a BLEVE is indeed responsible for the maximum damage distance (which is very likely). However, the fireball approach is a very simple one and does not include the various aspects to a fire(ball) following a BLEVE of a vessel containing pressurized liquefied flammable gas. Especially not of vessels with large contents.

Some considerations of LPG fireballs

From incidents in the past (Kingman, Tewksburry; see Chapter 5) and from the disaster in San Juan Ixhuatepec, evidence has been found to the effect that a rising fireball is preceded by a groundlevel fireball (also found in experiments). Certainly not all the liquid released upon a BLEVE will flash immediately to become part of the fireball. The violent release of energy upon rupture of a vessel also scatters part of the liquid about the surrounding area.

Especially in the case of very large amounts of LPG, released instantaneously, the effect of the LPG, cooling by the initial flash is expected to be significant. Mixed with air the LPG will heat and vaporize, but in the first instance there will be a lack of air to vaporize all liquid and for the same reason mixing with air to a flammable mixture will not occur.

What may have happened at San Juan Ixhuatepec is that a relatively large amount of unburned LPG was scattered about the built-up area (in the case of BLEVEs of larger vessels), while in the mean time mixing with air initiated burning. It may have entered the houses, causing internal explosions (photos 15, 18). An interview the TNO team had with the fire brigade of Mexico City revealed that the fire at groundlevel expanded enormously upon large explosions. When that happened the fire brigade had to run for their lives. It is possible that the diameter of the "groundlevel fireball" exceeded the diameter of the rising fireball in these cases. The formulae used for modelling a BLEVE fireball ((1), (2)) are mostly obtained from small-scale experiments. An extrapolation to situations involving large amounts of LPG can cause deviations. Baker [3] suggests that it is more rewarding to plot experimental test results and data from accidents as scaled fireball sizes versus scaled time histories, in order to obtain a single functional relationship. He also mentions that the transient fireball growth cannot be ignored.

The video tape of the San Juan Ixhuatepec disaster reveals a BLEVEtype explosion with a "fireball" lasting at least 90 seconds. In fact, the fire did not take the shape of a fireball but looked more like a huge flare ascending hundreds of meters into the sky. The fire was most likely fed for a time by a highly directional huge release of LPG.

Conclusions on fireball dimensions

- * The model for calculating a BLEVE fireball diameter, used in [1] and given in this chapter, predicts the maximum distance to which heavy damage occurred in San Juan Ixhuatepec reasonably well (with a slight underestimate). Formulae used in [3] give a more significant underestimate.
- * The transient growth and actual dimensions of (groundlevel) fireballs from BLEVEs involving large amounts of flammable material are not yet fully understood. Additional study is required.
- * The major damage in San Juan Ixhuatepec was probably caused by intense LPG fires, amongst others due to spreading of (liquid) LPG through the area.
- Damage distances for the smaller vessels cannot be verified:
 damage (distances) is exceeded by BLEVEs from the larger vessels.

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Other fires

Apart from fireballs in connection with a BLEVE, other fire mechanisms can be distinguished:

- 1. A fire, started by LPG scattered about the area, as described in the preceeding paragraphs.
- 2. A fire at the storage site, being fed by LPG from ruptured vessels and pipelines.
- 3. Fires due to propelling bullet tanks, releasing LPG in their flight or after crashing into the built-up area. However, after the crash fires did not occur.

It has become clear from photo material that very heavy fires occurred at the storage site. Eye-witnesses spoke of a very broad "wall of fire", high up in the sky. Apparently these fires were continuously fed by large amounts of LPG that came from ruptured vessels and pipelines. The fire on photo 25 is in fact divided into two parts. From a comparison of this photo with the one taken of the same location by the TNO team after the disaster, it follows that the fire originated from the spheres next to the two (remaining) largest spheres and the south-eastern part of the cylindrical storage tank area (series C, D and E; see figure 1.5.) or from the pipeline manifold at the back of the location. in question.

Effects on people and material covered by the fire

In most risk assessment studies it is assumed that human beings are highly unlikely to survive direct flame contact in an LPG fire. This theory is supported by case histories of incidents in the past and now also by the recent San Juan Ixhuatepec disaster. Most people living within a distance of 300 meters perished in the fire while they were still asleep in their homes. Photo material shows the difference between direct flame contact for some time and heat radiation. It has been difficult to draw conclusions in relation to heat radiation vulnerability models [12,14]. The relation between the damage distance and the time when the damage occurred is unknown. Therefore the connection between the extent of the damage and the extent of the fire remains unknown. A number of houses may have been destroyed by the fire. The huge fire and the BLEVEs lasted about an hour and a half. In cases of fire, concrete and bricks lose strength in about half an hour [13]. Several photos show concrete roofs and upper storeys that have collapsed, which may easily have been caused by the fire.

Heat radiation effects

Effect on people:

The heat radiation models used in [2] combined with the vulnerability model given in [12] and the model given in the preceeding paragraphs lead to the following limit distances for fatal injuries and first degree burns. This approach has been followed in [1].

Capacity of vessels	1% lethality	1% 1st degree burns
(m ³)	distance (m)	distance (m)
1600	925	1550
270	450	725
180	375	600
55	220	340
48	200	310
35	190	290

At this moment it is not yet possible to compare the calculated distances to the actual distances. This will only become possible when more data become available on the exact locations where people were killed and injured in the disaster area.

However, a comparison of the above-given distances with the actual damage gives the impression that the model leads to a significant overestimate of damage distances. This may be explained by the basis of the model: heat radiation on bare skin with no protection by objects between man and fire. The possibility of escape has also not been considered in this approach. A fair description of thermal hazards to human beings is given in [14]. In the course of 1985-1986 TNO will develop models of greater accuracy to assess the thermal radiation damage.

Effect on material:

Actual damage from heat radiation outside the heavily damaged area has been noticed by the TNO team:

- Leaves of trees were affected by heat radiation at distances of over 1200 m uphill (photo 26).
- In a street at 1200 m distance, plastic flags were shriveled because of the radiation (photo 26).
- Paint came off at distances of about 400 m.
- Glass damage occurred at about 600 m distance from the river (see photo 23).
- Glass damage and fires because of heat radiation (curtains, artificial grass) occurred at a house in Al Copal (600 m).

The heat radiation on the surface of LPG fireballs is normally taken at about $E = 200 \text{ kW/m}^2$ [2]. This entails that values of heat radiation of about 5 kW/m² at 1200 meters are possible for fireballs with diameters of 400-600 m [2]. The limits for values for the scorching of wood are about 8-12 kW/m² [13].

Glass may burst at values of 5 kW/m^2 [13]. Given this value, glass damage up to a distance of 600 m because of heat radiation is possible [2]. Further investigation may follow subject to availability of pieces of the scorched material (curtains, grass).

3.2.3. Fragments and missiles

Ruptures of vessels containing pressurized liquefied gas normally produce quite a number of fragments of the vessel. These fragments receive a specific kinetic energy as a result of the physical explosion. As has already been mentioned in 3.2.1., the blast wave is largely determined by the expansion of the vapour above the liquid. According to [2], 60% of the expansion energy is transformed into kinetic energy of the fragments. This kinetic energy turns the fragments into missiles which may be scattered over considerable distances. The velocity of (part of) a cylindrical bullet tank that is propelling from its position (in this particular disaster from a few meters up to 1200 meters) is determined by the counter-pressure of the released LPG (see also 3.2.1.). From this a first estimation of the distance range of a propelling cylinder (without any lift) can be made. In [16] a velocity of the vapour of about 60 m/s is mentioned for a flash evaporation of the contents of an LPG vessel. The weight of the LPG inside a cylinder is approximately identical to the weight of the cylinder itself. Thus a cylinder will drop at a distance of up to 360 m. This figure is not very reliable, it changes with the square of the velocity. It shows however, that the lift is a significant factor where considerable distances are involved because the vessels in question were propelled to distances of up to 1200 m.

The theoretical models, available for prediction of fragment ranges [3] are not very accurate either and a large number of assumptions have to be made. In Appendix 6 a calculation is given of the theoretical maximum distance for the range of fragments. Irrespective of the size of the cylindrical vessel, this particular distance amounts to about 2000 m. For fragments of spheres this distance amounts to about 3500 m. The vessel from which such a fragment originates has to be empty at the time of rupture. Moreover, the flying fragment (its size being rather irrelevant) needs a position where maximum ascent is possible at minimum resistance force.

No further theoretical calculations of fragment sizes and range prediction are given here; the models have not yet been developed far enough. Instead, the fragmenting at San Juan Ixhuatepec has been used in the statistical analysis, carried out in the past, of a number of incidents with failing vessels containing pressurized liquefied gas [10,11].

At the time of the TNO team's visit, a number of fragments had already been removed from the area. However, by the team's own observations, aerial photographs (a.o. a very detailed picture shown to the team by Pemex-IMP) and press photos, we assume that the majority of the major fragments have been traced by the team. The positions and distances of a substantial amount of smaller fragments are also known, but not given and used here.

Moreover, it has sometimes been difficult to distinguish between fragments from spheres and cylinders. It is possible that we have misconceived the origins of one or more fragments.

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The positions of the cylindrical bullet tanks and major fragments from spheres are given in figures 3.1. and 3.2.

The maximum distance over which a fragment travelled was about 1200 m. This was a bullet tank that had ruptured circumferentially ("end tub") and was originally part of the series of smallest cylinders (\emptyset 2 m, L = 13 m). This "end tub" destroyed two houses from which the inhabitants had already fled on account of the intense heat. From eye-witness reports it can be concluded that during its flight the bullet was rotating in a radial direction.

The maximum distance to which fragments of spheres have been found to travel was 600 m north of the site, in the El Copal area. This particular fragment landed on a big house (see photo 5). More photos of fragments are given (see Appendix 8).

The fire on the Gasomatico site initiated the explosion of a large number of gasbottles. Several bottle missiles were produced. An analysis of this effect was not possible due to lack of information. At least one bottle landed at a distance of about 500 meters.

3.2.3.1. Fragments of cylindrical bullet tanks

A description of the damage at the site is given in Chapter 2.2. However, it has not been possible to indicate the original position of the cylinders, but the I series (figure 1.4.) is on the correct spot. The majority of the tanks of the G series are also within their original bund. They were probably shifted by an explosion in the H series section. The same applies to 4 tanks of the H series (see figure 3.1.).

The mechanism responsible for repositioning the majority of the cylinders within the storage site, is a blast wave generated from explosions of other cylinders (see also 3.2.1.). All cylinders, which travelled more than 100 meters were "end tubs"; a few end tubs (3) could be identified at lesser distances. The weight of the end tubs has been calculated in the cases of smaller tanks. Depending on size, the weight of the (empty) tanks comes in the range of 20-25 tons. The distance range of cylindrical bullet tanks (centre of measurement is given in figure 3.3.):

	number of bullets	end tubs
On supports	4	
In their original bund	11*)	
Within 100 m	17	3
100 - 200 m	4	4
200 - 300 m	3	3
300 - 400 m	2	2
400 - 700 m	1	1
700 -1000 m	1	1
1000 -1200 m	1	1
		3 -3-3-3-3-3-3-3 -3
Total	44	15

*) two of them ruptured longitudinally

44 Tanks from a total of 48 could be traced. Apparently 4 tanks could not be identified. Most likely they were fragmented into smaller pieces. At least two of the major fragments could be identified as originating from a cylinder.

A preferential direction can be found in the position of the cylinders after the disaster. That can be expected for these end tub tanks, which travel in an axial direction. This preferential direction has been found before. The end tubs in this incident are plotted in a graph [11] (see also figure 3.7.).

The preferential failure of north-end heads of the tanks (giving them a southward direction) is probably caused by one-sided heating, coming from the fire of the ruptured pipeline connections at the north-side of the tanks.

The distance range of the cylindrical bullet tanks

The distance range of the tanks is plotted in figure 3.3. from [11]. It may be assumed that all end tubs have been identified. A noteworthy fact is that end tubs in Mexico City apparently travelled over greater distances than in other accidents. However, from [11] it does not become clear what exactly is meant by "LPG end tub event". Fragments of other "non tub" tanks are most likely included in [11], which may explain the difference.

The points in figure 3.3., indicating the ranges in Mexico City, have been calculated for a total of 15 end tubs. So a distance range up to a maximum of 500 m was reached by: 15-3 . 100 = 80% of the end tubs, and so on.

3.2.3.2. Sphere fragments

Number and weight of fragments

In [11] the number of fragments involved in various incidents with spheres have been plotted and correlated. These correlations mean that in the case of the Mexican incident the number of fragments (per sphere) probably ranged from 5 to 18 (see figure 3.4.). This amount seems reasonable, considering the sizes of the sphere fragments that have been identified (see also the different photos in this report). A number of 5 to 18 fragments have a calculated weight of about 10-40 tons.

25 major fragments could be identified; the position of at least 15 smaller fragments is known (mainly at the site). With an expected total of 20 to 70 sphere fragments, it can be concluded that maximal about 40% of the fragments have not been identified (see figure 3.5.).

Many eye-witnesses (see Appendix 3) spoke of a "metal rain" at the time of the heaviest explosions. This may be accounted for as the result of fragmenting of a great number of small metal pieces. However, this type of fragmenting is highly unlikely to occur in the case of incidents of this nature. Much higher overpressures (detonations) are required to set off such a fragmenting mechanism. In the case of sabotage with explosives, e.g. such heavy fragmenting may be expected. No small fragments were discovered by the team at the time of the visit.

Distance range of major fragments of spheres:

Distan	ce	Number
590	meters	1
500	- 590 m	1
400	- 500 m	3
300	- 400 m	1
200	- 300 m	7
100	- 200 m	6
100	meters	6
	Tota	1 25

Total number of major fragments and their range

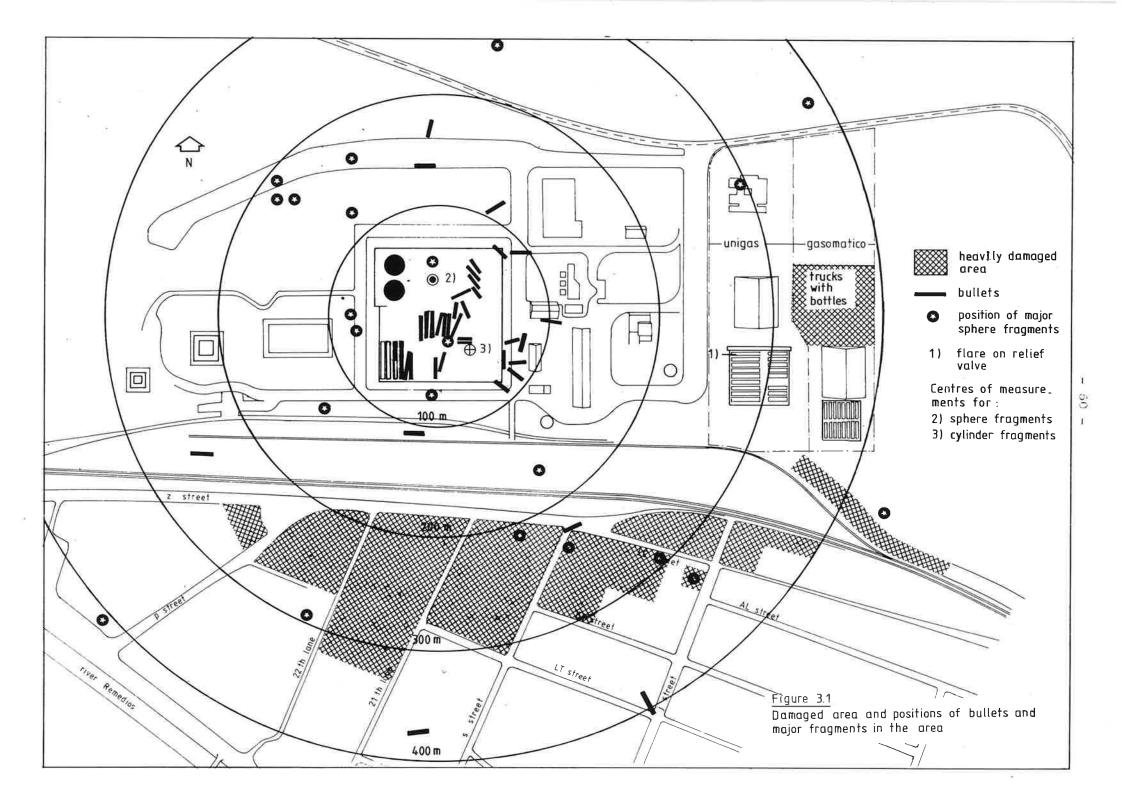
The total number of major fragments from spheres given above is 25. In an analysis of the range of every major fragment, end tubs are considered to be major fragments. In which case the total number of major fragments amounts to 40. This results in the points plotted in figure 3.6. [11]. Once more (as can be seen in figure 3.6.), this particular range of fragments is greater than has been plotted for other accidents, probably because smaller fragments have not been considered.

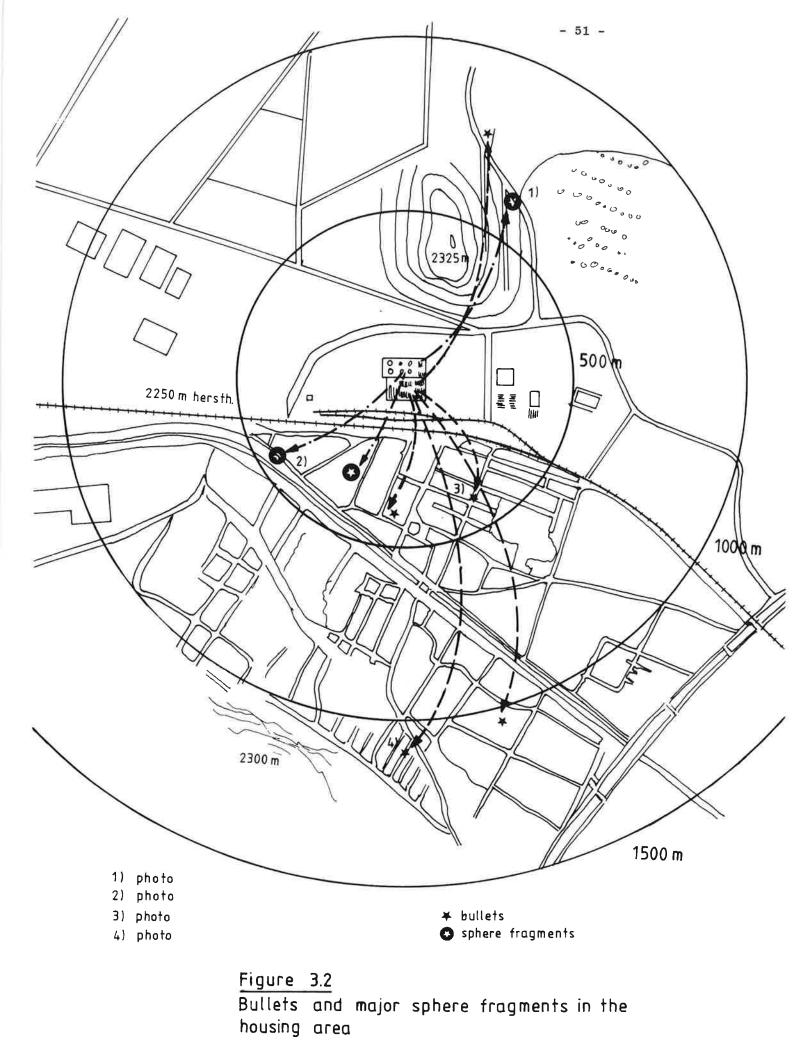
3.2.3.3. The potential of missiles to penetrate nearby vessels

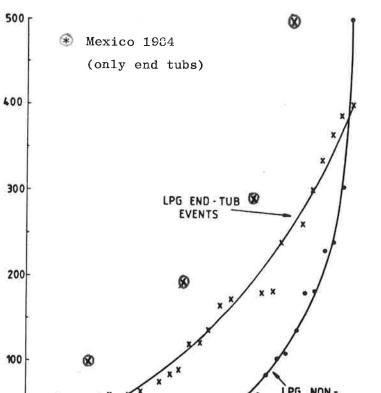
It is stated in 2.4. that fragments of exploding vessels could have penetrated nearby vessels ("domino effect"), in this way adding more LPG to the fire. The possibility of penetration has been calculated [15] (Appendix 7). From these calculations it follows that the velocity of fragments required to penetrate a nearby vessel amounts to about 4-12 m/s, depending on the weight of the fragment. The actual velocity of a fragment from a cylinder or sphere upon rupture and subsequent fragmenting of a storage tank depends on the volume of the vapour space of the tank, and on the shape of the tank (which determines the volume/energy efficiency).

The calculated maximum velocity of fragments from a cylinder is about 150 m/s, and about 200 m/s in the case of fragments from a sphere. When the vapour space is about 25% of the vessel, these velocities are reduced by a factor $\sqrt{0.25} = 0.5$.

The velocities required to penetrate a vessel are much lower than the actual ones. There is no doubt that penetration is possible, as can also be concluded from incidents in the past.







RANGE, R (m)

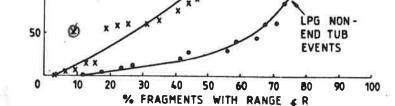
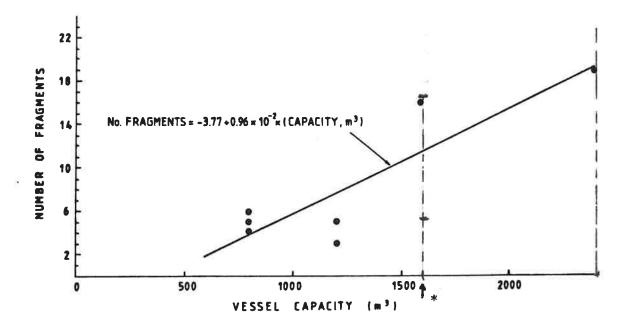
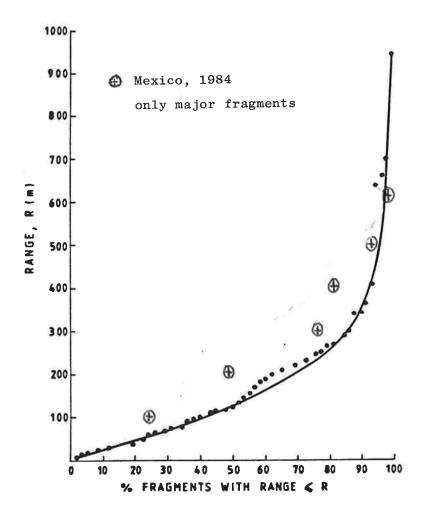


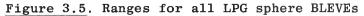
Figure 3.3. LPG events where all fragments and their ranges are known end tub / non-end tub events



* Sphere capacity Mexico

Figure 3.4. Correlation between number of fragments and vessel capacity for spheres (7 events)





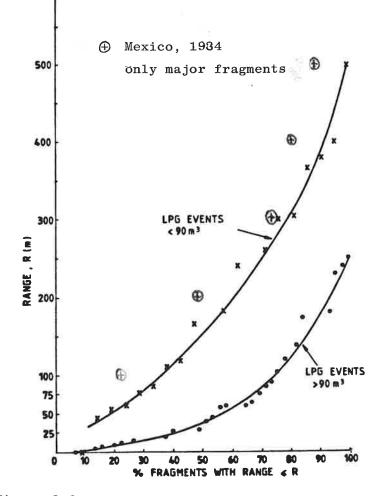


Figure 3.6. LPG events where all fragments and their ranges are known - vessel size - > 90 m³ / < 90 m³ events

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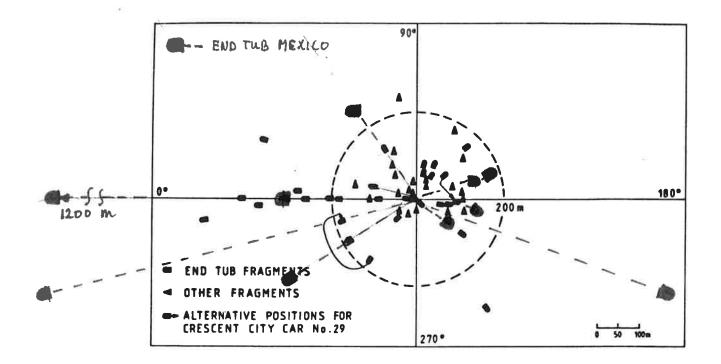


Figure 3.7. Correlation of fragment range and distribution for liquefied gas vessels

4. EMERGENCY HANDLING

On Monday, 19 November 1984, at approximately 5.45 a.m., the Mexico City fire brigade witnessed at large distance an explosion accompanied by a fireball. When the telephone started ringing shortly afterwards, the brigade had already left. So had personnel of other fire stations in Mexico City and surroundings.

In the meantime, the highway patrol had been alarmed and they implemented "Operation Vulcano". In conformity with this operation scheme, every highway that led to the disaster area was closed to all private traffic. The Secretary for National Defence implemented disaster scheme DN-111-E from his residence after some time.

The Central Military Hospital was instructed to open its doors to the incoming wounded at the same time.

In retrospect, the above report is the introduction to one of the major LPG (Liquid Petroleum Gas) disasters in history.

4.1. Scale of events

First of all, some rough figures must serve to illustrate the immense and complicated task the emergency services were faced with. An area of a few square kilometers was affected by the disaster, its extent ranging from complete destruction and minor fires, to scattered damage, caused by flying debris from exploding gas tanks. 150 homes were estimated to have been completely destroyed, a few hundred sustained damage of a different nature.

There were 500 dead and 7000 wounded, some of them with burns, in the area in question. Some 1000 people were more or less seriously affected. At least 200,000 people were evacuated during the course of the emergency operations.

The event took place within a timespan of 12-14 hours. 7000 emergency workers are thought to have been involved in this particular disaster. They were members of the fire brigade, the police, the army, ambulance personnel, subway personnel and many others.

4.2. Impressions of the actions conducted by the fire brigade

Only 30-45 minutes elapsed before the various emergency services, such as the fire brigade, the police and the ambulance services arrived on the spot. The magnitude of the fires, the heat radiation and the continuous threat of exploding gas tanks called for prudent action, which resulted in the fire brigade having to work their way into the village from outside. The fire was prevented from spreading, minor fires were put out and first aid was given where necessary. The second major explosion took place during these actions. Eye-witnesses spoke of a wall of fire and heat that was closing in on them and forced emergency personnel into a temporary withdrawal.

According to an interview by the press with a member of the emergency services, the rescue personnel had to work under dramatical circumstances. Rescue teams had to decide who was to be rescued and who was not. That is why hopeless cases had to stay behind in favour of victims with better chances.

The fire brigade was only after considerable time able to install jetsprays to cool the storage tanks at plants in the vicinity. Fortunately, the tanks in that area did not explode. Not after the situation at the neighbouring plants had been brought under control, were the fire brigade able to venture out into the grounds of the burning LPG storage and distribution centre, where they tried to put out the remaining fires and cool the undamaged tanks. The fire was brought under control at 3.30 p.m. and all remaining fires

had been put out at 8 p.m.

There were no casualties among fire brigade personnel. The water supply did not cause any problems, although water had to be supplied by water-carrying lorries as the Chiconautla pumping-station had been damaged by the explosions.

4.3. Impressions of the evacuation and the reception of the wounded

Most villagers of San Juan Ixhuatepec took flight towards the nearby highway, avenue Insurgentes Norte and surrounding hills, soon after the explosions and fires started. The first refugees arrived already at 6.15 a.m. at Indios Verdes subway station, situated 2-2.5 km away from the village. It appears that there was no organized evacuation during the first few hours. A chaotic phase, lasting for hours, had in fact been entered into, showing the familiar picture that belongs to major disasters and accidents.

It seems that chaotic scenes have become part and parcel in this respect, during the first few hours.

As many wounded as possible, especially those suffering from severe burns were evacuated in ambulances to nearby hospitals. At least nine hospitals, of which some are part of the Social Security Institute, are situated within a radius of 10 kilometers from the disaster area. Provisional relief centres, where first aid was given and a further selection of the wounded carried out, were set up some hours after the initial explosions, when the nearest hospitals became overcrowded with people. Over a thousand people were thus treated in the relief centre at the Basilica of Guadalupe, some 5 kilometers away.

Apart from the ambulances, buses, lorries and the subway were used to transport evacuees to makeshift camps, sports and health centres and to the Basilica of Guadalupe. 5,000-7,000 people, e.g. spent the night inside the premises of the National Polytechnic Institute. The operation was organized by volunteers and students. Private initiatives attracted lots of publicity in the newspaper reports. All sorts of collections, for food, clothing and footwear got under way after only a few hours. The goods were directly transported to the makeshift relief centres. There was such an accumulation of goods at the Basilica that some people even started trading in them.

To allow for a smooth transport of the wounded, a huge parking area for ambulances belonging to the various relief services was created off the river Los Remédios. Thus, space was reserved for water-carrying lorries and vehicles from other emergency personnel. Helicopters from "Operation Vulcano" assisted ambulance drivers in finding their way, and took some wounded people to distant hospitals. An authorized evacuation of the area got under way after some time. Over 200,000 people were evacuated. Many of them from Indios Verdes subway station. The evacuation did not take place without incident. Especially in more remote parts of the area, hundreds of people resisted having to leave their homes, in spite of the fact that the gas storage was still on fire.

At 2 p.m., only the dead remained in the immediate vicinity of the disaster area. An early mass burial was organized on the next day, to prevent the outbreak of epidemics.

Only 25 of the 298 dead (up till that moment) could be identified.

4.4. Some figures produced by the Ministry of Health

During the disaster 985 medics, 1780 para-medics and 1332 volunteers were giving medical assistance. They handled 7231 wounded of which 5262 were treated in provisional emergency centres. 1969 wounded were taken to 33 hospitals. Approximately 900 of them had to stay there for further treatment.

By the 25th of February 1985 710 patients have recovered, 32 were still in the hospitals and 144 people died there.

For transportation purposes, the emergency services used 363 ambulances and 5 helicopters.

Eleven provisional shelters were established for 39,000 homeless and evacuated people.

A number of 35,000 hot meals per day with a total of approximately 125,000 hot meals were provided.

4.5. Approximate time schedule

05.30 hrs	start of events
05.46 "	first major explosion
06.00 "	police close roads, first emergency personnel arrive
06.15 "	army implements disaster scheme
06.54 "	second major explosion
07.00 "	panicking, caused especially by live television
08.00 "	roads become congested with refugees
09.00 "	nearby hospitals become overcrowded
10.00 "	private help gets under way
11.00 "	end of explosions
15.30 "	fire under control
20.00 "	fire extinguished

5. HISTORY OF LPG-BLEVE INCIDENTS

Important BLEVE incidents which are comparable to the Mexican disaster (BLEVEs at an LPG bulk/storage depot) are given - from 1950 onwards - in this chapter.

The number of BLEVE incidents of this size that is given here is considered to be fairly complete for two reasons. First , large incidents cannot be kept secret and secondly, almost all relevant literature (see end of Chapter) has been gone through as a counter-check on the incidents stored in the TNO incidents database "FACTS". Almost all incidents in from literature were also found in FACTS. In most cases, FACTS gave a more detailed description of the incidents (reports) than the literature did, but in a few cases additional information was found.

In Appendix 7 a characteristic selection from FACTS is presented of all recorded incidents in relation to "BLEVE" and/or "FRAGMENT". Some noteworthy facts about the incidents in relation to the disaster in San Juan Ixhuatepec have been selected in this chapter. No conclusions or possible explanations are given here. The facts are used in Chapter 3 for reference.

5.1 <u>LPG-BLEVE incidents comparable to the incident in San Juan Ixhuatepec</u> BLEVE incidents are called "comparable" to the incident in San Juan Ixhuatepec when:

- relatively large LPG storage tanks on a bulk depot or refinery are involved, and
- * one or more BLEVEs have taken place.

The above mentioned incidents are listed in table 5.1.

5.2 BLEVE incidents (LPG) involving transport/handling, etc.

BLEVE incidents involving (mainly) transport systems are given, specifically in relation to the physical effects: fragmenting data and heat radiation data. These incidents are listed in table 5.2. Two incidents are described in more detail as some of their data are relevant to the analysis of the incident at San Juan Ixhuatepec. The incidents in question relate to a filling station for railway tankcars and to the unloading of a road tankcar.

Tewksburry, Massachusetts (US) 1972 [18]

Two half-empty propane storage tanks. A tank car starts to fill one of the tanks and leakage develops through mechanical damage. A vapour cloud ignited at the vaporizers. The fire started at 22.37 hrs and the tank car BLEVE-ed at 22.55 hrs.

It was estimated that about 24.6 m³ of propane was left in the tank at the time and about 13.6 m³ of flash vaporized and caused a huge fireball. The remaining liquid propane was scattered in every direction in burning and unburning form. The rear of the tank flattened out, whilst the front remained cylindrical and was propelled forward.. Grass and needles of trees were set fire to within a radius of 120 m. A shock wave caused various walls and roofs to crack, concrete walls came apart at the mortar joints and windows of buildings on the site were smashed. Burning liquid entered and set fire to these buildings.

Kingman, Arizona (US) 1973 [17,18,19]

Leakage of LPG from a railway tank car during unloading. The railway tank car BLEVE-ed after 40 minutes. Volume of propane at the time: 76 m^3 .

Initially a "ground level" fireball (D=90-120 m) developed, immediately followed by an ascending fireball: D=250-300 m. One part of a tank travelled 370 m. The other part flattened (open at the top). 95 people were injured (heat radiation) at 300 m. A nearby shopping center became engulfed by blazing fuel.

* The majority of the incidents started with leakage and a resulting vapour cloud. In most cases ignition occurred within a distance of 150-200 meters.
 No blast wave effects from vapour cloud explosions in open air

have been reported. The effects of overpressure in buildings have also been reported: walls were blown out from a building where ignition had occured (Cottage Grove, 1956) and explosions in pumphouses and other buildings took place (Montreal, 1957).

- * Severe blast wave damage has been reported from BLEVEs (Feyzin: 500 m). A great deal of damage to buildings resulted, but also: Spheres and cylinders were thrown off their supports (Rio de Janeiro, 1972). Tanks failed by missiles (Texas, 1978).
- * The noteworthy fact of a ground level fireball preceding a huge rising fireball has been mentioned (Kingman, 1973). In another case (Tewksburry, 1972) it was also reported that only about 35% propane flash vaporized (total volume of tank contents just before the BLEVE: 38 m³) and was integrated into the fireball. The remaining liquid propane was scattered about in every direction.
- * The majority of the cylindrical tanks apparently ruptured longitudinally, a number ruptured circumferentially (several incidents).

Large parts (single-headed cylindric shells) of cylinders that failed circumferentially are thrown away over considerable distances (maximum distance: 700 m, Mc Kittrict 1959).

- Heat radiation from a BLEVE: Maximum reported distances in cases of people injured: 300 m (Feyzin) Maximum reported distances in cases of people killed: 300 m (Kingman)
- * In several cases, spheres did not explode violently, but merely split at the top (Feyzin, Montreal).

*

* In one case it was reported that two spheres BLEVE-ed simultaneously (Montreal).

There are significant differences between the periods in which a
 BLEVE takes place after vapour (cloud) ignition:

1. 3 - 10 minutes (Newark, Montreal, McKittrict)

2. > 30 minutes (Montreal, McKittrict, Feyzin)

Group 1 probably relates to direct flame impingement BLEVEs (on vapour space).

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MAJOR LPG-BLEVE INCIDENTS AT DEPOTS/REFINERIES

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	Port Newark New Yersey (US) 1951 [17,18]	Cottage Grove Oregon (US) 1956 [17]
* Number/type/volume storage tanks involved	70 horizontal cylinders: 9 batteries of 6 to 12 tanks Dimensions: $\emptyset = 2.7$ m, L = 21.3 m	tank - 70 m ³
	(lay-out: see figure 5.1.)	
* Quantity of LPG involved	in total: ~ 11,400 m ³	< 70 m ³
* Cause	pipe rupture	leaking fittings or broken sightglass
* Ignition source	spark from broken pipe, directly after rupture (no vapour cloud)	in buildings with vaporizers/boilers
* Timing of the incident	3 min. flow from 3/4" pipe 3 min. after ignition: fireball 15 min. later: violent BLEVE next 100 min.: BLEVE's of 70 tanks	BLEVE 20 min. after first alarm
* Dimensions of fire- balls/damage distan- ces		wall blown out of vaporizer building
* Fragmenting: distances/type, weight of fragments	majority of tanks exploded longitudinally, a number circumferentially: 1 tank flew 800 meters away	
* Various	 6 batteries (70 tanks) destroyed 3 batteries were located at 107 m, only 3 tanks in that battery were destroyed. the shut-off valves operated adequately Fire continued for several days. 	non-ferrous risers/ caps on the safety valves melted and blocked the outlet

MAJOR LPG-BLEVE INCIDENTS AT DEPOTS/REFINERIES (Cont.)

	Montreal East Canada 1957 [18, 19]	Mc Kittrict California (US) 1959 [17]
* Number/type/volume storage tanks involved	3 spheres (common bund) 1 sphere 800 m³ 2 larger spheres	6 horizontal cylinders 25-60 m ³
* Quantity of LPG involved	Butane (relevant: outside temp.: - 6.7 °C boiling point butane: -0.5°C	1 propane tank(‡ full) 3 butane tanks(2 full) (2 gasoline)(‡ full)
* Cause	Overfill (level gauge failed)	failing nipple at drain connection
* Ignition source	A service station 183 m away	gas-powered engine at 15 m distance
* Timing of the incident	 liquid in bund (butane) large vapour cloud 10 min. after ignition: 1 sphere splits open 40 min. after ignition: BLEVE of 2 tanks (spheres) 	 flow from 1" opening after 1 min. ignition after 10 min.→BLEVE after 35 min.→all tanks failed (some violently)
* Dimensions of fire- balls/damage distan- ces	 1,5 km high flames (3180 m³ butane involved) explosions in pumphouses other buildings 	-
* Fragmenting: distances/type, weight of fragments	 a large number of missiles over a wide area a 27 mlong tank support → 358 m away 3 tanks with flammables hit at 46, 152 and 183 m 	first BLEVE: single head and the shell (3 meters) travelled about 700 m
* Various		first impingement on vapour space

MAJOR LPG-BLEVE INCIDENTS AT DEPOTS/REFINERIES (Cont.)

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	Feyzin France 1966 [17,18]	Rio de Janeiro Brasil 1972 [17,19]
* Number/type/volume storage tanks involved	4 spheres of 1200 m ³ 4 spheres of 2500 m ³ interspacing: 1 diameter each 4 spheres in bund: 0.25 m high. the 8 spheres in bund: 0.8 m high.	5 spheres of 1600 m³ 16 horizontal cylinders
* Quantity of LPG involved	butane/propane 50/50	all tanks failed. material: LPG
* Cause	sampling at drain- connection failed	draining left unattended (2")
* Ignition source	autoroute (car at 120 m.	-
* Timing of the incident	 flow from 3/4" pipe: 35 min. large vapour cloud 1 hr after ignition: BLEVE 1½ hr after ignition: BLEVE later 3 spheres split at the top 	 large vapour cloud beyond the refinery boundary the sphere BLEVE'd (> 20 min. later) 3 more violent explosions
* Dimensions of fire- balls/damage distan- ces	 blast damage: 500 m. firemen at 300 m killed by BLEVE (3/4.2000 m³) 	 tremendous blast wave from first BLEVE: spheres and cylinders thrown off their supports
* Fragmenting: distances/type, weight of fragments	 sphere split in 5/6 fragments pieces of steel up to 100 tons travelled 100 m. one fragment landed on a pipeway: 40 lines cut piece cut from the legs of an adjoining sphere. 	. many refinery buildings: blast damage
* Various	shell spheres: 1.7" thick max. inside press: 1.176 psi.	 fixed water system on the spheres cylinders: monitor nozzles and hydrants

	Texas-City Texas (US) 1978 [17,19]	New York (US) 1979 [17]
* Number/type/volume storage tanks involved	<pre>12 tanks: 1 sphere 800 m³ 5 cylinders (hor.) of 160 m³ 4 cylinders (vert.) of 160 m³ rest unknown</pre>	5 tanks (85% full)
* Quantity of LPG involved	11 tanks failed	
* Cause	unidentified	mechanical failure of filling line by snowscraper
* Ignition source		pilot flame of vaporizer
* Timing of the incident	 < 5 min. after fire: BLEVE of sphere within next 20 min.: 9 cylinders + 1 sphere failed through missiles or BLEVE's 	2
* Dimensions of fire- balls/damage distan- ces		
* Fragmenting: distances/type, weight of fragments	. butanetank: 300 m away . fragments up to 1.5 km	 shell of 8 m long: 65 m away the rest in opposite direction: 370 m
* Various		before accident: . gas smell at 240 m . fire water-spray system failed.

MAJOR LPG-BLEVE INCIDENTS AT DEPOTS/REFINERIES (Cont.)

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MAJOR LPG-BLEVE INCIDEN	TS AT DEPOTS/REFINERIES, (Cont	•)
	Mexico-City 1984 (see for more details chapters in this report)	
* Number/type/volume storage tanks involved	4 spheres of 1600 m ³ 2 spheres of 2400 m ³ 48 horizontal cylinders of different sizes	
* Quantity of LPG involved	almost full (85%) with propane and LPG	
* Cause	pipe leakage in cylinder area	
* Ignition source	burner at the Pemex site	
* Timing of the incident	 vapour cloud developed 5.45 ignition 5.46 first BLEVE with a violent explosion (2 spheres 1600 m³ and -2 cylinders?) 8 violent explos. in 5/4hr. 	
* Dimensions of fire- balls/damage distan- ces	 severe damage outside the s by (BLEVE's) up to 300 mete glass damage up to 600 mete cylinders thrown off their 	rs rs (heat radiation)
* Fragmenting: distances/type, weight of fragments	 fragments thrown in a wide area (mainly < 300 m.) complete cylinders (missing single head), launched to several locations: 100,200, 400,m and 1.2 km. 2 largest spheres only split at the top 	
* Various		

MAJOR LPG-BLEVE INCIDENTS AT DEPOTS/REFINERIES, (Cont.)

Year/place/ literature	Material	Quantity	BLEVE	Fire	Heat radiation	Fragmentation
1958 Celle (BRD) [17,20]	LPG	45 m³ wagon	explosion	+		wagon of 2 tonnes smashed against wall to 150 m distance
1968 Dunreith (US) [17, 20]	ethyleenoxide vinylchloride	5 wagons	1 rail tankcar with ethyleenoxide	÷	obstructed fire brigade	dome of tank propelled to a distance of 400 m.
1969 Laurel (US) [20]	LPG	15 wagons	several explosions during 40 minutes		23 m high flare 2 huge fireballs	tank fragments up to 500 m
1970 Illinois (US) [17,20]	propane	9 wagons of 64 tonnes	5 wagons	fireball	300 m high fire- ball	one 12 tonnes tank propelled to a distance of ± 500 m
1971 Houston (US) [17, 20]	vinylchloride	6 wagons of 183 m³ each	fireball with a diameter of 300 m			tank propelled to a distance of 122 m
1972 Tewksburry (US	see Chapter 5.2.					
1973 Kingman (US)	See Chapter 5.2.					
1974 Oneonta (US) [17,20]	LPG	7 rail tank- cars of 113,5 m³ each	4 rail tankcars	safety relief valve		fragments up to 400 m

Table 5.2. BLEVE incidents (LPG) involving transport/handling etc.

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Continued

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Table	5.2.	cont.
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Year/place/ literature	Material	Quantity	BLEVE	Fire	Heat radiation	Fragmentation
1975 Iowa (US) [17,20]	Propane butane	11 wagons	4 wagons	fire- balls		Fragments up to 300 m
1977 Dallas (US) [17, 20]	isobutane vinylchloride LPG		1 wagon			Fragments up to 170 m
1978 Waverly (US) [20]	chlorine propane	3 wagons 2 wagons	+	+	Fireball	Fragment of 9 tonnes propell to distance of 70 m

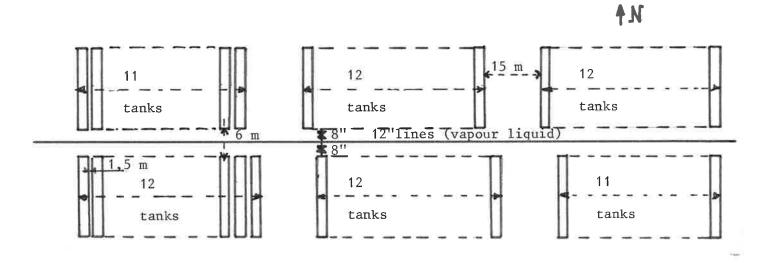


Figure 5.1. Lay-out of Port Newark facility,

all tanks: ϕ 2.7 m, L = 21.3 m, supported by 2 concrete saddles.

6. CONCLUSIONS

Some preliminary conclusions are drawn in this report. Follow-up studies may lead to some more detailed conclusions, both on effect and damage models and on safety aspects in relation to (large) LPG-storage sites.

The main purpose of this accident analysis is a check of existing effect and damage models, currently used in risk analysis studies. With respect to this check, the following is noted:

- * The prediction of possible overpressures of vapour cloud explosions in a certain environment is not yet possible. Although from incident analyses by others [4] a certain degree of confinement has been found as a necessary condition for significant overpressures, this condition is not sufficient. It is likely that no significant overpressures were generated by the vapour cloud combustion in the built-up area of San Juan Ixhuatepec, although a certain degree of confinement was present. This justifies the use of a probability which is lower than one for significant effects of overpressure following a vapour cloud ignition. This approach has been followed in [1]. Moreover, it stresses the need for further development of the explosion models.
- * The effects of overpressure of the physical explosion following ruptures of the LPG-storage vessels in San Juan Ixhuatepec were determined by the expansion of the vapour phase in the tanks. Overpressures of sizes calculated with the flash evaporation models could not be identified. It is confirmed that higher LPGliquid temperatures are required to generate those overpressures.
- * When it is assumed that the fireball resulting from a BLEVE is the mechanism that determines the damage upon rupture of a LPGstorage vessel in fire situations, the damage distance found in San Juan Ixhuatepec is comparable with the damage distance found with the model applied in [1].

It is further concluded that the damage mechanism is not just a (lifted) fireball. In case of large storage vessels the expanding groundlevel fires, in combination with spreading unburned LPG, may determine the damage distance. Additional studies on the growth of the fireball and the resulting damage distances are desirable.

* The effects of heat radiation from fireballs at greater distances from the storage site did not lead to many fatalities. It is highly unlikely that fatalities did occur at distances greater than 500 m. That means that mitigating factors at greater distances should be taken into account in case protection (housing etc.) is present. This is usually not done in risk analysis studies [1]. It will only result in a slight overestimation of the number of fatalities because a fatality criterium of 1% is used outside the projection of the fireball up to the 1% fatality distance. The maximum fatality distance however, is significantly overestimated in those cases.

In relation to the site and location in San Juan Ixhuatepec, the following preliminary conclusions are drawn:

- * The close lay-out of the storage site may have contributed to the fast escalation of the incident.
- * The large amount of fatalities and injured people in San Juan Ixhuatepec is a result of the fact that the built-up area is situated close to the LPG-storage site, and the very high population density in that area. The housing was chiefly built after the construction of the LPG facilities.
- * The position of the cylinders determines to a large extent the preferential direction in which the cylinders - that landed at distances greater than 100 meters - were launched. The position of the pipe connections at the vessels is probably also significant in this respect.

With regard to the emergency services, the following can be concluded:

* The emergency services were faced with a very heavy task in the first chaotic hours. The sequence of events was so very fast, that the services had to respond immediately on full capacity. This task was performed quite well: within 6 hours all injured people had been transported to hospitals. Generally speaking it can be stated that emergency services should take into account a fast development of accidents of the type that occurred in San Juan Ixhuatepec.



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Appendix 1





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APPENDIX 1

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PRESS BULLETIN ATTORNEY GENERAL



PROCURADURIA GENERAL DE LA REPUBLICA DIRECCION GENERAL DE COMUNICACION SOCIAL

BOLETIN DE PRENSA

488/84 México, D. F., a 22 de diciembre de 1984

La Dirección de Servicios Periciales de la Procuraduría de la República rindió informe sobre los hechos ocurridos el 19 de noviembre pasado en San Juan Ixhuatepec, Estado de México.

Para la elaboración de su informe, los peritos oficiales reunieron y valoraron diversos elementos de juicio, -que con detalle constan en la documentación de las diligen- cias practicadas.

Del análisis realizado se desprende que el sinies-tro que destruyó la planta de Petróleos Mexicanos y que direc tamente causó daños personales y patrimoniales mayores en San Juan Ixhuatepec, se produjo a partir, principalmente, de un sector de tanques horizontales de la planta de Petróleos Mexi canos, ubicado inmediatamente frente a los depósitos esféri-cos.

En este siniestro hubo deflagración como consecuencia de una fuga masiva de gas que presumiblemente tuvo su pun to de ignición en un quemador de la planta de PEMEX, y tam-bién se registró explosión de tanques y otros artefactos.

Considerando que estos hechos dieron lugar a los -daños referidos, la empresa paraestatal entregará a las auto-

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translation see page 1.4 ridades respectivas, bajo un concepto de responsabilidad social objetiva, la cantidad necesaria para efectuar los resar cimientos ya iniciados por daños materiales en los bienes, así como para cubrir indemnizaciones por lo que toca a las consecuencias consistentes en daños personales. Para definir los montos individuales de estos últimos, se utilizará como indicador o punto de referencia el criterio establecido por la Ley Federal del Trabajo. Estas liquidaciones se realizarán sin perjuicio de los pagos que, en su caso, deban -hacer las empresas aseguradoras a las que se alude en este comunicado.

La destrucción prácticamente total de la planta de Petróleos Mexicanos en San Juan Ixhuatepec y la muerte de la mayoría de los trabajadores de PEMEX que se encontraban de guardia el 19 de noviembre, priva de algunos datos que serían de suma utilidad para precisar con mayor exactitud las características del siniestro. Sin embargo, existen suficientes elementos para sustentar una opinión técnica con razonable grado de probabilidad, sin incurrir en afirmaciones categóricas que pudieran carecer del debido fundamento.

Para los fines del informe, se hicieron diversas visitas de inspección; se realizaron los exámenes y las valo raciones que el asunto requiere, confórme a su carácter espe cífico y a su complejidad; se recibió y estudió la declara-ción de más de un centenar de testigos presenciales, entre los que figuran algunos trabajadores de PEMEX y personas ajenas a este organismo; y se tuvo a la vista el material -disponible acerca de la operación y el mantenimiento de la planta de PEMEX, proporcionado oportunamente por la empresa,

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que incluye los señalamientos formulados por la correspondiente comisión mixta de higiene y seguridad industrial.

Los peritos trabajaron en estrecha coordinación con la Procuraduría de Justicia del Estado de México y requirieron la intervención, en algunas o en todas las etapas de su estudio, de técnicos que laboran en diversas dependencias oficiales federales, como las Secretarías de Comercio y Fomento In-dustrial y de Energía, Minas e Industria Paraestatal. Se reci-bió amplia y constante atención por parte de autoridades y funcionarios técnicos de Petróleos Mexicanos.

Petróleos Mexicanos hizo entrega de la documenta- -ción en la que se analizan los problemas de mantenimiento ord<u>i</u> nario de esta planta, y se concluye que aquéllos no pudieron causar por sí mismos los hechos sujetos a examen. Dicho aná-lisis forma parte del conjunto documental con el que se inte-gra el informe.

En virtud de que la planta de Petróleos Mexicanos, al igual que las demás instalaciones industriales de esta empresa, se halla cubierta por seguro contra destrucción y daños a terceros, los peritos que elaboraron el informe continuarán la revisión total de los hechos conjuntamente con los técni-cos de las empresas aseguradoras, dentro del propósito de exa minar con la mayor profundidad las diferentes hipótesis planteadas y emitir un dictamen final.

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Translation of second and third paragraph of p. 1.1.

It can be deduced from the investigation that the disaster, which caused the destruction of the Pemex plant and which directly resulted in great damage to people and goods, was chiefly initiated c.q. created in the sector where the horizontal tanks at the Pemex facilities were situated. This sector directly faces the spherical storage tanks.

During this disaster deflagration occurred as a result of a large escape of gas which probably was ignited by a burner of the Pemex facilities; tanks and other installations exploded as well.

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APPENDIX 2

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SOME RESULTS OF AN ANALYSIS OF 165 VAPOUR CLOUD EXPLOSIONS

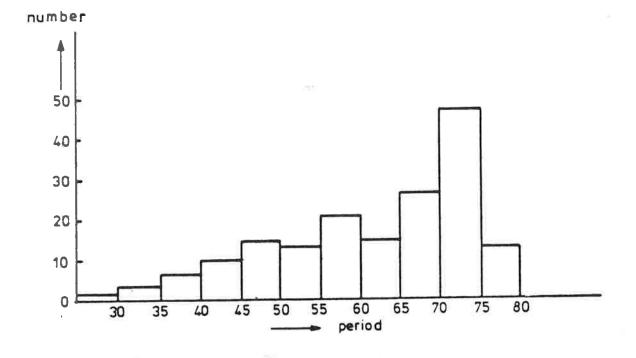


Figure 1. Number of registered ignited vapour clouds in periods of 5 year.

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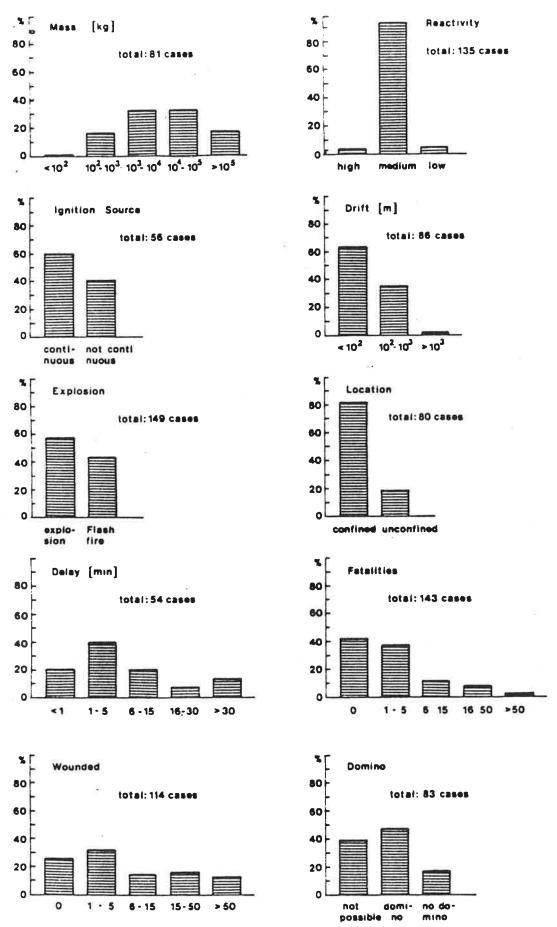


Figure 2. Relative percentages of occurrences of the selected features.

Appendix 3

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APPENDIX 3

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DATA FROM THE TNO INCIDENT DATA BASE "FACTS"

				ADDRESS			
				PORT NEWARK, NEW JERSEY		11	EXPLOSION AND FIRE OF 70 TANKS
3914	1955	0719	Ð	LUDWIGSHAFEN		2	EXPLOSION AND FIRE TANKWAGGON
4255	1956	0729	USA	AMARILLO, TEXAS	20	532	BLEVE OF 3 OIL TANKS
			USA	COTTAGE GROVE, OREGON	12	12	BLEVE OF LPG STORAGE TANK
			CDN	MONTREAL	1		OVEFLOW BUTANE SPHERE
			D	CELLE	7		EXPLOSION TANKWAGGONS
				MC KITTRICT, CALIFORNIA		2	EXPLOSIONI STORAGE TANKS
		0104		FEYZIN	18	40	EXPLOSION OF TANKS AT REFINERY
				DUNREITH, INDIANA	10	10	BLEVE OF TANKWAGGON AFTER
0704	1700		CON	PORTELITY INFIRM			DERAILMENT CAUSED BY BROKEN RAIL
307	1969	0125	USA	LAUREL, MISSISSIPP1	2	33	DERAILMENT OF TRAIN WITH 15 TANKWAGGONS, EXPLOSION AND FIRE
7624	1969	1203	NL	UNKNOWN			RUPTURE OF TANK BY FIRE
		0621		CRESENT CITY, ILLINOIS		65	
							OF 9 TANKWAGGONS
373	1971	1019	USA	HOUSTON, TEXAS	í	50	DERAILMENT OF 18 TANKWAGGONS EXPLOSIONS AND FIRE
3891	1971	i118	NL	NIEUWENHOORN			EXPLOSION OF CYLINDER CAUSED FIRE OF DEPOT
3655	1972	0209	USA	TEWKSBURRY, MASSACHUSETTS	2	21	
							LINES OF TANK CAUSING BLEVE OF STORAGE TANK
681	1972	0330	RŔ	RIO DE JANEIRO	37	53	
001		0000	1. C	NTE DE DIMETRO	07	20	BALL TANK
2521	1973	0705	USA	KINGMAN, ARIZONA	13	96	EXPLOSION AND FIRE OF LPG
							DISTRIBUTION PLANT
671	1973	33 33		NEW YORK			RUPTURE PIPELINE OF STORAGE TANK, BLEVE OF TANK
2549	1974	8111	USA	WEST SAINT PAUL, MINNESOTA	4	6	EXPLOSION OF TANK
2544	1974	0212		ONEONTA, NEW YORK		25	
667	1974	0417	Ø	BIELEFELD, BRACKWEDDE			DERAILMENT OF 36 TANKWAGGONS, FIRE. EXPLOSION AND BLEVE
7527	1974	1202	NI	HAARLENNERMEER-RIJSENHOUT		1	
		8622	USA	ANGLETON, TEXAS		•	BLEVE OF 79.28/M3 TANK
			USA	DES MOINES, 10WA		3	
				·			TANKWAGGONS
		825		LOOSDRECHT	2211		FIRE AND EXPLOSION IN CAR
3918	1976	0 8 31	USA	GADSEN, ALABAMA	3	28	EXPLUSION TANKVEHICLE AND STO- RAGE TANKS DURING TRANSSHIPMEN
2071	1976	1126	USA	BELT, MONTANA		22	DERAILMENT AND EXPLOSION OF SEVERAL TANKWAGGONS
4137	197 7	0206	USA	BOYNTON BEACH, FLORIDA			BLEVE OF LPG CYLINDERS CAUSED BY DERAILMENT FREIGHTTRAIN
669	1977	0220	USA	DALLAS, TEXAS		1	DERALLMENT OF TANKWAGGONS
		0423		LONG ISLAND, NEW YORK	1	5-0.	BLEVE CYLINDERS ON LORRY
	1977			HAWLEY, PENNSYLVANIA	Mac 1		FIRE AND BLEVE OF TANK ON TAR
1							HEATING CAR
25 22	1977	0519	USA	POCONO MOUNTAINS, PENNSYLVANIA		í	LEAKAGE SUPPLY LINE CAUSED EXPLOSION VAN
35 9 5	1977	<u> </u>	NL	MARKELO			BLEVE OF TANK OF ASPHALT WILLING MACHINE

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CC‡ -	YEAR-DATE	- VOTINO V	ADDRESS	
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				ADDRESS		INJS	SCENE
	1978			WAVERLY, TENNESSEE	15	43	
21 19	1978	0530	USA	TEXAS CITY, TEXAS	7	10	11 TANKS EXPLODED BY UNKNOWN CAUSE IN 45 MINUTES
209	1978	1218	NL	NIJMEGEN			BLEVE OF TANKVEHICLE AT FUEL- STATION DURING TRANSSHIPMENT
2736	1 9 78	1220	NL	ZWOLLE			EXPLOSION OF GASCYLINDER IN MEASURE-CAR
1591	1979	0516	NL	VLAARDINGEN		2	FIRE IN VAN AND EXPLOSION OF GAS CYLINDER
1639	1979	0601	NL	'S GRAVENZANDE			EXPLOSION OF GAS CYLINDER During fire in barn
1634	1979	0704	NL	OOSTFLAKKEE			EXPLOSION OF 2 CYLINDERS AND 1 OILTANK
2575	1979	0713	NL.	RUTTERDAM			EXPLOSION OF CYLINDER IN VAN
1630	1 9 79	0817	NIL.	DE HEERN			OVERHEATING OF KETTLE WITH TAR CAUSED EXPLOSION OF GAS CYLINDER
953	1979	0908	USA	PAXTON, TEXAS		8	DERAILMENT OF 33 TRAINWAGGONS WITH CHEMICALS, EXPLOSION AND FIRE FOR 2.5 DAYS
1560	1979			HAARLEHMERMEER			EXPLOSION OF TANK IN CAR
1181	1980	0105	NL	ROTTERDAM		1	FIRE IN BUSSTATION, LPG TANK EXPLODED
1166	1980	0108	NL	ERLECON, RIVER WAAL		2	COLLISION OF TANKER "KOMBI 21"
							AND VESSEL "RODORT 6" EXPLOSION, FIRE
3922	1980	0303	USA	LOS ANGELES, CALIFORNIA	2	2	OVERTURN AND EXPLOSION TANK- VENTCLE LOADED WITH GASOLINE
				ROTTERDAM			FIRE IN FACTORY STURE
				RAALTE			FIRE IN MOTOR COMPARTMENT OF CAR, BLEVE OF TANK
				ROAD BREDA TO BAVEL			MOBILE MILLING MACHINE WITH GASTANK EXPLODED
1520	1980	1126	NL.	OOSTERWOLDE -		1	EXPLOSION OF TANK IN CAR DURING ASSEMBLE
3419	1980	3333		KREIS BORKEN - WESEKE		5	FIRE AND EXPLOSION OF TANK- VEHICLE
1836	1981	0302	NL	WIERDEN			FIRE AND EXPLOSION OF GAS CYLINDERS IN STORED CARAVANS
2052	1981	0409	NL	APELDOORN			FIRE OF CARAVANS NEAR LPG INSTALLATION
2092	1981	0510	NL	HAARLEN			FIRE AND EXPLOSION OF STORAGE BRAN
2504	1981	0713	NL	BEUNINGEN		1	EXPLOSION OF GASCYLINDER IN HOUSE
2560	1981	0816	NL	OLDEHOLTPADE, WOLVEGA		1	EXPLOSION OF GASTANK IN CAR BY COLLISION
3988	1981	12 ??	NL	TIEL			V.W. TRANSPORTER ON FIRE, TANK EXPLODED
4350	1981	?? ??	USA	UNKNOWN	13	17	BLEVE OF CYLINDER IN CONVERTED COACH
\$53 5	1981	3353	GR	YATELY, HAMPSHIRE			EXPLOSION OF CARTANK IN GARAGE

		DATE		ADDRESS	FTLS	INJS	SCENE
7640	1982	0113	NL	ALKMAAR Den haag			FIRE AND RUPTURE OF CYLINDER EXPLOSION OF A PLUMBER GAS CYLINDER
3960	1982	0601	NL	HAARLEN			EXPLOSION OF A GASCYLINDER
3972	1982	0621	NL	GROOTBROEK	1		CYCLING PERSON HIT FATALY BY FRAGMENT OF CYLINDER
4354	1982	0626	CDN	BLAIRMORE, ALBERTA			DERAILMENT AND RUPTURE SEVERAL. TANKWAGGONS
		0916		UNKNOWN			RUPTURE OF GASTANK IN CAR BY FIRE
				LIVINGSTON, LOUISIANA			DERATLMENT FREIGHTTRAIN BY OVERSPEED
		???? 0315				19	FIRE AND EXPLOSION OF GAS PIPELINE PLASTIC DEFORMATION OF TANK
		0709		UNKNOWN			DUE TO OVERHEATING BY FIRE RUPTURE OF A CAR TANK DUE TO
		0723		ROMEOVILLE AND LEMONT, ILLINOIS	15	22	FIRE EXPLOSION AND FIRE AT REFINERY
	1984	0921	NL	BRUCHTERVELD, HARDENBERG	क ग	an, dan	RUPTUKE OF CYLINDER DUE TO BACK FIRE OF FLAME

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			CNTRY	ADDRESS			SCENE
				PORT NEWARK, NEW JERSEY		11	EXPLOSION AND FIRE OF 70 TANKS
224	1957	0108	CDN	MONTREAL	1		OVEFLOW BUTANE SPHERE
	1958			CELLE		2	EXPLOSION TANKWAGGONS
				MC KITTRICT, CALIFORNIA		2	EXPLOSION STORAGE TANKS
	1966			FEYZIN	18	40	
3709	1768	0101	USA	DUNREITH, INDIANA			BLEVE OF TANKWAGGON AFTER DERAILMENT CAUSED BY BROKEN RAIL
307	1969	0125	USA	LAUREL, MISSISSIPPI	2	33	DERAILMENT OF TRAIN WITH 15 TANKWAGGONS, EXPLOSION AND FIRE
361	1970	0621	USA	CRESENT CITY, ILLINOIS		66	DERAILMENT AND EXPLOSION OF 9 TANKWAGGONS
373	1971	1019	USA	HOUSTON, TEXAS	1	20	DERAILMENT OF 18 TANKWAGGONS EXPLOSIONS AND FIRE
3891	1971	1118	NL	NIEUWENHOORN			EXPLOSION OF CYLINDER CAUSED FIRE OF DEPOT
3655	1972	0209	USA	TEWKSBURRY, MASSACHUSETTS	2	21	COLLISION TANKVEHICLE WITH LINES OF TANK CAUSING BLEVE OF STORAGE TANK
681	1972	<u>;;</u> ;;	BR	RIO DE JANEIRO	37	53	EXPLOSION AND BLEVE OF A BALL TANK
2521	1973	0 705	USA	KINGMAN, ARIZONA	13	96	BLEVE OF TANKWAGGON CAUSED EXPLOSION AND FIRE OF LPG DISTRIBUTION PLANT
2549	1974	0111	USA	WEST SAINT PAUL, MINNESOTA	4	6	EXPLOSION OF TANK
2063	1975	0901	USA	DES MOINES, IOWÀ		3	DERAILMENT AND RUPTURE OF TANKWAGGONS
669	1977	0220	USA	DALLAS, TEXAS		1	
	1977			LONG ISLAND, NEW YORK	í		BLEVE CYLINDERS ON LORRY
6 10	1978	0222	USA	WAVERLY, TENNESSEE			WAGGONS CAUSED BY BROKEN WHEEL
2119	1978	0530	USA	TEXAS CITY, TEXAS	7	10	11 TANKS EXPLODED BY UNKNOWN CAUSE IN 45 MINUTES
919	1980	0902	NL	ROAD BREDA TO BAVEL			MOBILE MILLING MACHINE WITH GASTANK EXPLODED
5535	1981	????	GB	YATELY, HAMPSHIRE			EXPLOSION OF CARTANK IN GARAGE
3972	1982	0621	NĹ	GROOTBROEK	i		CYCLING PERSON HIT FATALY BY FRAGMENT OF CYLINDER
	1984			ROMEOVILLE AND LEMONT, ILLINOIS	15	22	EXPLOSION AND FIRE AT REFINERY
8235	1984	0921	NL	BRUCHTERVELD, HARDENBERG			RUPTURE OF CYLINDER DUE TO BACK FIRE OF FLAME

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APPENDIX 4

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A SELECTION OF NEWSPAPERS AND MAGAZINE REPORTS FROM THE DAYS DIRECTLY AFTER THE DISASTER

(a)

APPENDIX 4

A SELECTION OF NEWSPAPER AND MAGAZINE REPORTS FROM THE FIRST DAYS AFTER THE DISASTER

The scope of this study required analysis of the daily and weekly papers that were issued shortly after the disaster. A list of those that were consulted is included at the end of this chapter.

An extensive selection of reports containing relevant information has been drawn up. Relevant information in this respect has been broadly interpreted, because the reports in question may later be used for other (social, psychological) studies.

A selection of reports of primary importance for the course of the disaster - on the subject of the plant, the destructive effects of the disaster and the relief work - has been included in this Appendix

Because, as a matter of course, many papers printed the same reports, those that were first read, form the majority. The purpose of this selection has been the prevention of overlap.

Also included are those eye-witness reports of people who were in the area when the disaster took place.

It must be stressed that the degree of objectivity rests with the person who carried out the translation and selection:

- 1. S. Cendejas, Ph.D. (TNO), the first selection.
- 2. J. Muezerie (Min. Int. Affairs), the second selection; the translation of relevant paragraphs from the reports.

The press material is used as "background information". It presents some rough indications. The facts given are never to be considered "true" (as in fact they are not true in a number of cases).

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19	November	1984	(1st	edition)	
19	**		(2nd	edition)	
21	November	1984			
22	11				
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LIST OF CONSULTED NEWSPAPERS AND WEEKLY MAGAZINES

Excelsior Wednesday, 21 November 1984.

p. "Está Apagado"

José Delgado Zacarias (approx. 50 years old), who is an employee of Ruta 100, and a resident of Privada Tlalpac 9, Lomas de San Juan, the outer limits, where large fragments of the gas tanks came down, narrated: "It was just after three in the morning when I had to go to the w.c. and smelled gas. I went outside into the street and noticed that the pilot flame at the Pemex plant, which is supposed to burn day and night, had gone dead and was hissing louder than usual. I went back into the house and spoke to my wife: "Pray, the whole thing is not going to explode", although I thought at the time that it was just part of a normal routine. However, then came the big bang."

Other people too, confirmed they had also noticed a strong smell of gas coming in from the north over San Juan that morning. The people also mentioned a day-time fire at the plant, when only wood is supposed to have been burnt, 5 months ago.

The majority of the inhabitants of San Juanico are natives, who went there in hope of a brighter future. San Juanico numbers 35,000 people; 75,000, if those who live on the bare hills are included. Most roads are unpaved and the valley is shrouded in an eternal cloud of dust. Drinking water has to be supplied through donkeys or lorries. The rainy season changes San Juanico into a mud-pool. Public transport is extremely unreliable, forcing schoolchildren and workers who have to go to Mexico City to return in invariably overcrowded 3rd class carriages, late at night, when women especially run all sorts of risks. Housewives are dependent on a small poor market. There are only a few primary and secondary schools. The river Los Remédios streams through the valley, its waters black and smelling, whereas they used to be clear as crystal. Garbage and the eternal cloud of dust are everywhere.

Excelsior Friday, 23 November 1984.

p. 19A.

At Unigas, the damage was limited to the head-office, which was struck by a huge fragment - weighing 40-50 tons - from a spherical gas tank.

The 20 storage tanks, each containing 50,000 liters, situated about 40 meters from the sub-station, were only blackened by smoke. Neither these tanks, nor the filling-station and the 60 smaller, filled gas-containers, ready for distribution, exploded.

The main event however, took place at the site of Gasomatico, where the damage was extensive. The fire destroyed nearly 100 lorries, loaded with cylinders weighing 20 or 40 kilos each. A two-storeyed building was also damaged. The filling-station, 20 meters away, with at least 300 cylinders, was left intact, as were the 20 storage tanks with a capacity of 250,000 liters each.

La Prensa Wednesday, 21 November 1984.

José Socorro told: "Everything smelled of gas, and that is what caused these balls of fire that were coming down the streets, spitting their fire, reducing the houses on one of the banks of the river Los Remédios to ashes."

p. 25.

Survivors reported that a strong smell of gas had been hanging over the area from Sunday-night on. On Monday, at 5.35 a.m., a violent explosion in one of the storage tanks, preceded by a heavy earth tremor, started off the disaster.

The fire penetrated the houses and scorched people who were just about to start their daily routines. Scores of families were not allowed time to run for safety.

4.4

La Prensa Wednesday, 21 November 1984.

p. 27.

The thousands of casualties were transported in ambulances from the Red Cross, the ISSSTE, the IMS, the rescue service, the SUEM, and in lorries from Ruta 100. People suffering from severe burns were taken to the nearest hospitals, the I Octobre Hospital, Urgências de la Villa, the National Medical Centre and La Raza included.

Hundreds of other casualties were taken to Tlali Sports Centre, Santa Cecilia, the City-hall of Tlalnepantla, the 18 March Sports Centre in the Federal District and also to the municipality of Ecatepec.

p. 44.

Eye-witnesses agreed that the fire that was caused by the first explosions reached a height of 500 meters. An area of one square kilometer was caught in a thick cloud of fire, igniting anything in its path. When the explosions finally subsided, a spherical storage tank, emitting an eighty meter high flame, slowly descended.

Uno más Uno Wednesday, 21 November 1984.

The telephone that started ringing at 5.45 a.m. at Frey Servando Teresa de Mier fire-station of Mexico City, turned out to be the first anonymous call for help. Seconds later, the telephone of at least 15 small-town fire-stations, Cuernavaca, Toluca and Pachua included, began to ring as well. The Federal Highway Patrol implemented "Operation Vulcano" at exactly 6 a.m. The scheme prohibited private traffic from using the highway that links Mexico City to Pachua, as well as the section that runs from Texcoco to Lechería.

At 6.14 a.m. reporters and photographers are already on the spot at San Juan Ixhuatepec.

Uno más Uno Wednesday, 21 November 1984.

Cont.

They witness a second, heavier explosion than before. The sea of flames its tangeringe colored column quickly reaching a height of 500 meters, initially spreads downward and reaches several blocks of houses built around the Pemex plant. The people inside the houses, animals, furniture were turned into a charred mass. Tanks that had exploded were flying through the air.

7.31 a.m.: The sixth gas explosion more or less alerts the fire brigade to stand by for action. Thereafter, a number of minor explosions follow at intervals of 30 minutes, the final one at 11 a.m.

8 a.m : The church-bells of the dwellings around San Juan Ixhuatepec are ringing incessantly. Inside a devastated area of two square kilometers, the fire brigade is working to prevent the fire from spreading. Some gas stations, the feeding-station included, remain unaffected by the disaster. 3.30 p.m.: The fire brigade has succeeded in reducing the fire at the storage plant where gas is still burning.

8 p.m.: The fire brigade has put out the fire in San Juan Ixhuatepec, but is maintaining the safety cordon.

Uno más Uno Saturday, 24 November 1984.

p. 27.

Telésfore Nava Vázquez believes Pemex ought to shift its "timebombs" to areas outside the city limits, especially in the case of the refinery in Azcapotzalco.

A large number of other incidents at the Pemex plant in less densely populated areas claimed less casualties:

- 11 dead at the Pemex refinery in Acahpan in the Federal State of Tabasco on 21 April 1984;

Uno más Uno Saturday, 24 November 1984.

Cont.

- 10 dead and 30 wounded, caused by an exploding Pemex poliduct near Mexico City in 1982.
- 52 dead and 21 wounded from a gas-main explosion in Magallenes in the Federal State of Tabasco.
- 16 dead and 150 wounded on account of an exploding gas-lorry near Mexico City.

The number of people injured at the Ixtoc disaster and in other incidents connected with the winning of oil must be included to complete the list.

Uno más Uno Sunday, 25 November 1984.

p. 2.

Mexico City and interurbia are supplied with gas through 31 private gas companies. Seven of these companies, in the vicinity of the terminal, have temporarily been put out of business, whereas five have been back in operation since 23 November.

Alarma (No. 1128) 12 December 1984.

p. 5-6.

Until the publication of this edition, three hypotheses about what started off the disaster have been put forward:

- A fire broke out at Gasomatico, destroying over a hundred lorries before spreading out to adjoining plants through the underground network of pipelines.
- 2. The pilot-flame at the Pemex storage and distribution station went dead on Friday night, causing gas to leak into the grounds, which sufficed for a tiny flame to set off the disaster on Monday morning.

3. Excessive pressure in the storage tanks caused the explosions and the resulting fires.

These are only hypotheses, the Attorney General to the Republic will have to reach a verdict, based on studies that are in progress at the devastated Pemex station, as well as at the almost undamaged Unigas and Gas Uribe plants. It is worth mentioning that experts from the Attorney General's office found a score of discarded, used fire extinguishers at Gasomatico's parking area.

The signs point to Pemex as the agent responsible for the explosion. Jésus Torres Alvarez, safety co-ordinator at Unigas stated on Thursday, 22 November, three days after the disaster, that the first explosion at the Pemex plant took place after one of the pipelines had leaked. The fact that only minimal damage, caused by fragments of Pemex tanks, was sustained at Gasomatico and Unigas is self-evident.

Alarma succeeded in interviewing one of the survivors, Roberto Solís Castro, of c/Acquiles Serdán no. 31:

"At exactly 5.40 a.m., I heard a violent explosion and at the same time flames penetrated the house. I heard people scream and when I realized what was happening, that the lives of the members of my family were in danger, I grabbed my wife and children and we made off as quickly as we could. We all suffered minor wounds from burning. On our way out, we saw that the people who had fallen down had been reduced to ashes."

Novedadez 21 November 1984.

Sections that were destroyed by the flames were the filling stations and a pumping house which used to have 8 pumps with a capacity of 36 gallons per minute and were used for draining and filling activities. The plant also had fire-fighting systems, consisting of a waterring with sensors and a sprinkler system in the filling station, pumping house and another waterring at the filling place for the gas tankcars.

4.8

El Universal 22 November 1984.

Pemex said that the fire in March 1984 was outside the plant. It occurred at a timber depot, where 60 tons of wood were burned. Then the sprinkler system at the plant worked perfectly, spitting around curtains of water around the 6 big spheric gas tanks. The fire outside was killed and there were no explosions inside the Pemex gas plant.

El Heraldo 21 November 1984.

Ixhuatepec, a ghost town. Rosa Ballonez, a young woman (20) left her house for school at 5.30 a.m. She told that she felt a blast which pushed her in the back and threw her against a car which was parked 10 m off. Her body was bruised all over. Lying on the ground she could hardly breathe, but was still able to see the inferno ahead of her.

Around 5.40 a.m., an enormous explosion rocked the town of Ixhuatepec.

Ultima Noticias 19 November 1984.

The Mexico City Electricity Board reported that the three transmission lines of 23,000 volts each had been affected. 200,000 people were cut off from electricity supply in the northern part of Mexico City. They explained that until 5.40 a.m. the LPG supply from the four plants feeding the Ixhuatepec gas plant had been blocked off, because supervisors had noticed that nobody answered their hourly routine check-up calls at the Ixhuatepec gas plant.

Antonio Espinoza left his house at 38 Lerdo de Tejada at 5.30 a.m. "I opened the door to bring out my ice cream pushcar, when suddenly there was this hot, red light. I was pushed in the back and fell down. I heard a terrible noise and everything became engulfed in a cloud of smoke. I was still on the ground when I heard another explosion; everything was rocking. I looked at my watch, it was 5.45 a.m. The second explosion was followed by a third one. Heat waves set everything on fire." Alejandro Roges, of 37 Avenida Remedios, one km from the plant, told that he was still asleep when suddenly flares penetrated the house. He immediately woke his family and they ran naked out of the house.

A journalist of U.N. visited the disaster area. At least 500 houses were completely destroyed and another 2000 were partly damaged.

The first explosion was such a violent one that it was taken for a volcanic eruption. The shock wave of the "earthquake" smashed many windows, even from houses at distances of several kilometers. A huge, 600-meter-high flare was followed by explosions with intervals of 30 or 40 minutes.

El Universal 21 November 1984.

A succession of explosions occurred as the fire engulfed the plant. A large, cylindrical gas tank went flying through the air with the second explosion and came down, 200 meters away, on several houses where people were killed either by fire or falling debris, or because they were crushed by the heavy tank. This particular cylinder struck a house at Lerdo de Tejada and 20 Noviembre, killing 21 people.

Although the fire had been brought under control, chiefly because the pipelines leading to the gas plant were blocked off, there was no sign of the flares subsiding. Fresh firemen arrived at the area and relieved their exhausted colleagues, some of whom were asphyxiated to a small degree. Firemen arrived from Mexico City, the State of Mexico, from Puentla and Hidalgo, from the airport and the Pemex plant, and even from the Forestry Service.

A journalist of E.U., who claimed to be the first one to arrive at San Juan, told that when he was walking about the area he saw the dead, charred body of a bus driver who was still clutching the steering wheel of his bus. The bus was about to start its daily route from San Juanico to the Indios Verdes Metro station, when the tragedy started. A second explosion again rocked the earth. Flames charred everything. With the second explosion one of the big storage tanks was blown away over a distance in excess of one km.

Pemex insisted that the piping system, running through the gas plant, had been blocked off, together with the valves that link the gas plant with the Atzcapatzalco refinery and other industrial sites in the State of Mexico.

There was an increasing danger that the two remaining large spherical gas tanks might explode and there were also the big cylindrical car tanks and a large number of portable gas tanks to consider. Over a hundred gas tank cars, their drivers included, as well as workers at the gas plant were consumed by the fire. Approximately 200 persons were killed there at the time of the disaster.

Additional explosions, 16 altogether, created panic and fear among the people in the suburbs.

The fire destroyed the electricity supply lines. The whole area was cut off from electricity supply, as was reported by the Federal Commission for Electricity.

San Juan Ixhuatepec is situated at the foot of the Copal and Chiquihuite.hills. Juana Herrera lives near the top of Chiquihuite hill. She told that she woke up at 5 a.m. as usual, to start her work. She noticed that the sky was on fire. "I fell on the floor and when I looked down the valley I saw a fireball leaping through the town till it was stopped against Copal hill. It was burning down lots of houses on its way." She thought of her daughter and son-inlaw who would certainly be dead. Later, at about 6.10 a.m., the sky turned orange and another explosion occurred.

Several cylindrical gas tanks were thrown through the air by the force of the explosions. They fell on top of houses, extending the burning area.

Unimas Noticias 19 November 1984.

- * Initial blaze at 5.40 a.m.
- * Jesus Torres, head of Security of Uni-Gasomatico.
- * Alejandro Reyes of Avenida Remedios 37 was still asleep when the flames penetrated his house.

Novedades 21 November 1984.

- * 3 Pipelines:
 - Minatitlan, 12", 80,000 barrels a day, 50% was intended for Tula.
 - Poza Rica, 4", 5000 barrels a day.
 - Atzcapotzalco, 4", 5000 barrels a day.

La Prensa 22 November 1984.

The heroic behaviour of a fireman and the stubborness of a boy saved the lives of 17 people at Benito Juarez 52.

Excelsior 21 November 1984.

Last sunday, a strong smell of gas had been hanging over the area according to people who had been injured.

The area most seriously affected by the explosive waves emitting from the giant cylinders containing approximately 5 million liters of LPG, was a strip on the Lazaro Cardenaz, where a block in excess of 200 houses - for the greater part built of wood, cardboard and sheets - was demolished by the raging fire.

Everything was thrown into confusion. The fire swallowed anything in its path, 8 trucks which were parked more than 400 m off included.

The army and the police gradually managed to evacuate the people. In the hills surrounding Ixhuatepec, hundreds of people were walking about. The Mexico City Council (DDF) requisitioned dozens of buses from public transport in order to evacuate the unharmed people from the village to some provisional shelters in schools and sports centres.

The commander-in-chief of the Mexican army had ordered that <u>Plan DN-III</u> was to remain in operation until new orders were issued. The team was working according to a plan named "Volcan", which was designed by the Federal Highway Patrol to assist the population in the case of disasters.

Helicopters from the "Operation Volcan" were flying over the area to assist ambulance drivers in finding escape routes and they also transported some injured people to hospitals further removed from Ixhuatepec.

Nicanor Santiago, a 45-year-old mason, tells his story. Around 5.30 a.m. I went to work. It was still dark when I took my bicycle out of the house, when suddenly there was this huge light, red and hot. I could not see anything at all. The huge light blinded me. I could not feel anything except that everything was hot. Then I heard some explosions and a second blast. The walls of my house were rocking, it was an earthquake. I was lying on the pavement and close to me all sorts of matter came falling out of the sky. There was a lot of broken glass, chairs and flower pots were flying all over the place. At first I thought an aeroplane was falling on our house, but I could not care less what it was. My wife and children were my only consideration. I suddenly remembered the PEMEX gas plant and I saw a big tongue of fire and a very big orange mushroom, and then I noticed another explosion. Pieces of molten metal were dropping out of the sky and I felt intense heat waves burning my clothes and my hair. I ran into the bedroom, everything was dark inside and there was plenty of smoke. I could not see anything. I could not breathe for the gas. I noticed that something huge fell on top of the house and a rush of air threw me out of the house into the street. By then I was really frightened and I started to run as fast as I could. I do not know where my wife and children got to. They may even ben unidentified in the mass grave".

Hermelinde Gomez tells her story:

Around 6.00 a.m. the whole town had become an inferno. At home everything was rocking. I heard cries coming from my parents, brothers and uncles. We were with 9 persons altogether. I did not realize what was going on. I only saw people running. It was still nighttime but the light from the fire was so intense that it could have been noon. I shouted to my relatives but they did not seem to listen. I took a blanket and went out into the street where I saw people running in despair. In between the explosions, a great noise resembling an aeroplane could be heard, I believe that it was the gas. I started to run and stepped on a corpse, it was a shocking experience. I smelled burning flesh and I thought I was going mad. I walked on and on until someone from the rescue team brought me to the church. I cannot remember anything else. I still have not found my relatives."

A member of the rescue team tells his story:

"We arrived at San Juanico at 6.15 a.m. We were the first to arrive. We did not know what was going on, when suddenly I became submerged in a veritable inferno. I thought it was the end of the world. People were running frantically in the streets. A great cloud of smoke was moving amidst a great noise that was like a whistle coming from a big monster. We heard cries of pain and noticed a penetrating smell. We were just starting to go to the people's assistance with some members of the rescue team when another heavy explosion threw us to the ground. Fragments of hot and molten metal were flying about like bullets through air. In spite of the lights of the fire the environment became shrouded by a cloud made up of smoke, earth, dust and gas.

4.14

As soon as the heat allowed us to see, we witnessed a terrible drama. From a house in the street of Lerdo de Tejeda, a complete family on fire emerged. As soon as they spotted us they came running towards us. We were profoundly shocked, they looked like mummies and their flesh was coming off in pieces.

The rescue teams decided who were going to be rescued. That is why some of the really seriously hurt people were left to die in the streets because they were considered beyond saving.

La Prensa 21 November 1984.

A story by José Hernandez:

"I went to the market to open my shop at 5.30 a.m. After a few minutes a terrible noise, followed by an earthquake, started everything off. The sky was red and there was fire everywhere. When I arrived at my shop I heard an explosion followed by an earthquake. I saw fire in the sky. Several houses caught fire, dogs were barking and running loose.

I grabbed a piece of wood to protect myself from the fire and ran back to my house that was on fire. I shouted for my wife and children to come out, but they did not listen to me. I grabbed a bucket and threw water on the sheets of the house. As soon as I had managed to kill the fire I went inside and I found my scorched family." As a matter of fact, under the debris of the house the bodies of his wife Felisa, 30, and his four children, 10, 7, 4 and 2 years old, were discovered.

In the "Cul de Sac" of 20 Noviembre, the same José Hernandez went accompanied by a journalist to the spot where his family had died. The 11 bodies were still there. In the house next door, a family of 10 had been killed. To finish the story, José Hernandez said that the worst affected streets were: 20 de Noviembre and Lazaro Cardenas.

It was 5.35 a.m. when the first explosion at the Pemex LPG distribution plant located in San Juan Ixhuatepec, produced an artificial dawn. Thousands of people were awakened by a noise which was followed by an earthquake which rocked the lining houses and smashed windows and doors. In the distance, over a red horizon, a column of fire was linking the earth to the sky, while hundreds of people were leaving their houses with their children in their arms.

The worst affected area was the street of Lazaro Cardenas in San Juan Ixhuatepec. Over there, tens of houses that belonged to the poor were engulfed by flames scorching the inhabitants, some still in their beds, others lying on the floor in their efforts to survive. Complete families died in deadly embrace of one another. Some ran out into the street out of desperation and pain and fell down on the pavement.

In the mean time, many survivors were running away naked, with bleeding feet, leaving traces of blood on the road.

Before sunrise, hundreds of Red Cross ambulances, rescue vehicles, personnel from the social security Institute (IMSS), civil servants from social security (ISSSTE), Pemex, SUEM and LASSER and many more were bringing in the injured people in an efficient way at the nearby hospitals.

The Eagles of the Secretary for Protection and Traffic - SPV (Police of Mexico City), the assistant manager of SPV stated that the helicopters from SPV had been transporting medicine, blood and other essentials for treatment of the injured since the morning of the tragedy to the La Villa Ranch, where the emergency medical centre had been set up. The injured were taken from this emergency centre to the various hospitals in Mexico City by ambulances from the Red Cross, the IMSS, the ISSSTE, the SSA and the DDF. A police spokesman said that it had not been possible to count the number of victims thus far.

A few hours after the accident, those affected who had come to the Basilica of Guadalupe had already been dressed and fed. They were still talking about the disaster: Everybody agreed that it had been like a deluge of fire. Tongues of fire everywhere, setting fire to the undergrowth, bedrooms, trees, grass, food, telephone and electricity cables. According to those who had already risen before 6.00 a.m., the sky had suddenly been on fire. It had been like being up at noon, everything had been so clear. Besides, had also been the heat, coming from the fire of the gas tanks, emitting mushroom-shaped clouds. The explosions, fires, earthquake and the full extent of the tragedy, made people shout and cry on the verge of nervous breakdowns. People who ran away from the fire sometimes had to retreat because it was coming at them from every direction. We were stopped by the fire on our way out.

Transported by ambulances and vehicles from the police, public and private rescue teams, thousands of victims managed to get away and gradually gathered at the "Indios Verdes" subway station, the gardens in the middle of Insurgentes Norte Avenue or at the courtyard of the Basilica of Guadalupe. The sun was still behind the mountains at the time, but the day had already broken. At these spots, half-naked people could be dressed in clothes spontaneously donated by people who live near the church.

There was such organized disorder, that rescue team officials did not know what to do with the people who had come to the Basilica to distribute food and clothing. Because large groups of people were gathering around those who were handing out the clothes, officials stopped the process to try and avoid benefitting people who had not lost anything. "Some are even going to open a shop, since they have been given so much". That is why they stopped handing out several tons of clothing which had already been collected over there. When one of the locals offered his house for use as a warehouse, several tons of food and clothing were stored over there. To give everybody a chance, aid started to be given in alphabetical order.

After having been out of their houses for two days (19 and 20 November) people wished to return but they were not allowed to. They were told that the army and the police would not let them in. That is why they gave up and waited for the following Wednesday at the latest to return to their dwellings. Approximately 500.000 people inhabiting 15 zones of the Ualnepantla district were evacuated.

The people who from burns almost all over their bodies had been transported to nearby hospitals such as the Primero de Octobre, Urgencies of le Villa, National Medical Centre and La Roga. The evacuations appeared to gon on and on. A stream of buses from Mexico City's Public Transport, together with ambulances from every emergency service was kept coming and going. Hundreds of unharmed victims were take to several sport centres. At the makeshift relief centres, those victims received all kinds of attention from good willing people. Hundreds of injured people received medical attention at different relief centres. Men, women and children suffering from second and third degree burns were treated by docters at the Basilica of Guadalupe. There, lying on blankets, Rafael Martinez, a 6-year-old boy told the press: "I was at the w.c. when I heard a heavy explosion. I woke my parents and brothers. We all went out and ran away from the house. On our way metallic objects on fire were falling on us. Ixhuatepec had become an inferno."

Some women suffered from a partial paralysis of their arms and legs due to extremely high blood pressure causing breathing problems and changes in pressure (SIC) because of intense emotional shock. Oxygen was administered to some of the women who had fainted.

Carolina Guttierez was going to buy milk when she heard a heavy explosion sounding like a bomb. "I was frightened", she said. "I kept close to the wall but suddenly my legs got caught in the flames. I ran back home where my husband was already waiting for me. Together with the children we ran away uphill."

José Socorro said that after the initial explosion, everything was rocking, as happens in the case of an earthquake. Fire was coming in from every direction. There was a smell of gas in the air; it rained fireballs, and in the streets you could see tongues of fire burning down the houses at one side of the river Remedios. We saw it all happen while we were climbing the hill.

After 17.00 p.m. on Tuesday, coffins were put into ambulances, hearses and plain lorries, and a mourning parade started to move towards Caracoles Cemetery close to Ixhuatepec, where practically all casualties of the disaster were buried. It was already getting dark when the parade arrived. Two great holes, each with a length of 150 m had been dug out of the hillside. Although the coffins were put in a mass grave, there remained a space of 20 cm between them. In this way the authorities were able to put a number on each coffin. Each number corresponded to a classification made by the forensic services. This system enabled relatives to see whether they were putting flowers on the grave of a child or on the grave of an adult. There were hardly any tears. In the previous 36 hours all tears had been shed.

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APPENDIX 5

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PRESSURE WAVE EFFECTS OF PHYSICAL EXPLOSIONS

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APPENDIX 5

PRESSURE WAVE EFFECTS OF PHYSICAL EXPLOSIONS

According to Baker et al. [3], a first estimate of the maximum blast wave effects of a BLEVE can be made, concerning the volume of the free vapour space of the tank. Reid [7] has indicated a minimum superheat level for propane, below which the estimate of Baker et al. will apply. The temperature limit is $\sim 55^{\circ}$ C (328 K). The vapour pressure of propane at that temperature will be ~ 18 atm.

A margin of 20% between the set pressure of safety values and a possible bursting pressure of the vessel gives a bursting pressure of 13,4 bar abs. Since this is below the superheat limit, we will follow the model of Baker et al. [3].

Vapour space volume

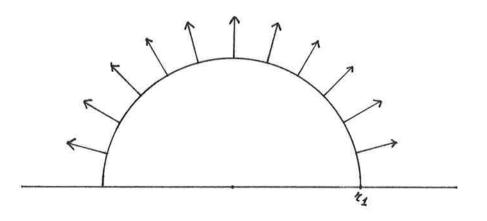
The volumes of the LPG vessels at the Pemex plant ranged from less than 100 m³ to 2400 m³. The actual liquid content of each vessel at the moment of BLEVE is unknown. Calculations for a scale of free vapour space volumes V_1 ranging from 20-

Calculation of relevant blast wave parameters

 2400 m^3 (20 - 100 - 800 - 1200 - 2400 m³) have been made.

To predict the damage caused by a blast wave, the peak overpressure and the specific impulse of the blast wave are relevant. These parameters are diminishing functions of distance from the centre of the blast wave. If it is assumed that the vapour space volume amounts to half a sphere at ground level, the air shock pressure at the sphere radius r, at the moment of bursting can be calculated [3].

It follows, that the maximum overpressure at the contact surface P is \sim 3.2 bar abs.



The radius, r₁, follows from

$$\mathbf{v}_1 = \frac{2}{3} \prod \mathbf{r}_1^3$$

The energy scaled radius follows from the energy released:

$$E = \frac{P_1 - P_0}{\gamma_1 - 1} V_1 \qquad (see [2,3])$$

with $\gamma_1 = 1,13$ and $P_0 = atmospheric pressure$

From the Yellow book [2] it follows that approximately 60% of the expansion energy is absorbed by the fragments of the vessel; so 40% contributes to the pressure wave. The energy-scaled radius of the sphere, \bar{R}_1 , follows from

$$\bar{R}_{1} = \left(\frac{3(\bar{\gamma}_{1} - 1)}{0.4 \cdot 2\Pi(\frac{P_{1}}{P_{0}} - 1)}\right)^{1/3}$$

which is a modification of equation 2-27 in Baker et al. [3].

For the considered cases, $\bar{R}_1 = 0.232$. From figure 2-14 in [3] (see figure 2), the corresponding curve for $\bar{P}_{so} = \frac{P_{so}}{P} = 3.2$ and $\bar{R}_1 = 0.232$ is found. The peak overpressure at distance r is found by following the curve to $\bar{R} = r/ro$ with

$$r_{o} = (\frac{0,4(\frac{P_{1}}{P} - 1)V_{1}}{\gamma_{1} - 1})^{1/3}$$

and reading $\bar{P}_s = (p - p_o) p_o$

The results for the different values of V_1 and r are given in Chapter 3.

Appendix 6

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APPENDIX 6

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THEORETICALLY POSSIBLE MAXIMUM FRAGMENT RANGE

APPENDIX 6

THEORETICALLY POSSIBLE MAXIMUM FRAGMENT RANGE

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Fragment kinetic energy [2]:
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$$\frac{1}{2}MV^2 = 0.6 \cdot \frac{P_1 - P_0}{\gamma - 1} \cdot V_{max}$$
 (1)

M = weight of vessel $P_{1} = bursting pressure of vessel$ $P_{0} = surrounding pressure$ $\gamma = C_{p}/C_{v}$ V = volume of vessel

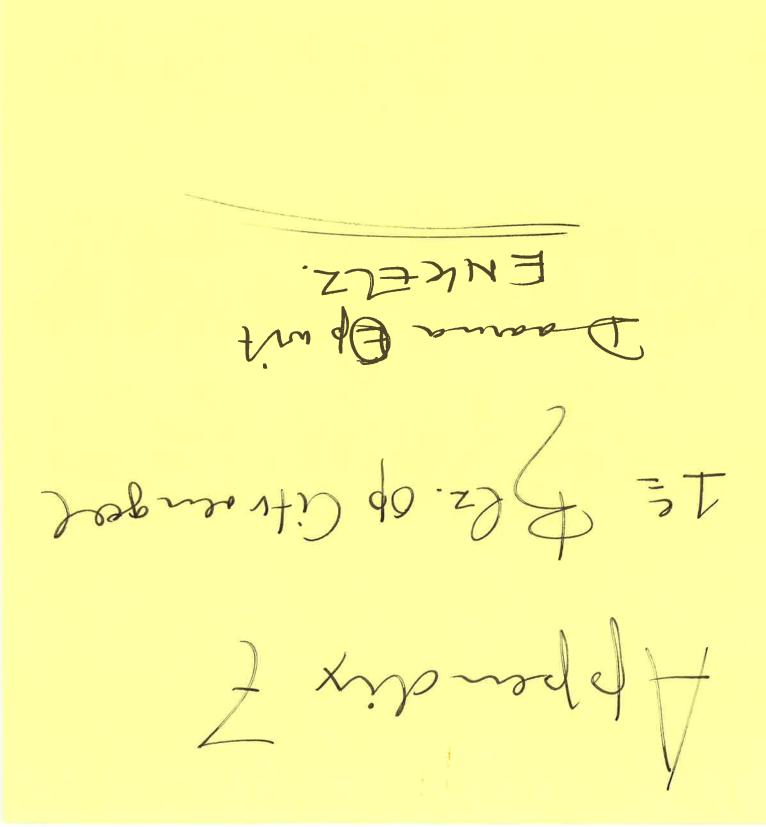
The calculation with (1) leads to the following results (using data from chapter 3.2.1.) for the different vessel sizes at San Juan Ixhuatepec.

V (m ³)	M (10 ³ kg)	V _{max} (m/s)
36	9.15	147
45	11.5	150
54	13.5	151
180	48	146
270	70	149
1600	215	206
2400	300	214

The maximum initial velocity of the fragments is:

- 1. cylinders: \sim 150 m/s
- 2. spheres : $\sim 200 \text{ m/s}$

According to [3], cylinder fragments of \pm 1 m² and 5 m² (flat plate) fly, under prime conditions (maximum lift, minimum resistance), to distances of about 2000 m. In the case of sphere fragments the absolute maximum distance is about 3500 m.



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APPENDIX 7

6)

MISSILE IMPACT

MISSILE IMPACT

Consider the possibility of a fragment arising from the BLEVE of one of the spheres or horizontal vessels striking a sphere. To pierce the sphere the fragment would have to land with a sharp point or edge against the sphere surface in order to concentrate the loading in a small area.

Since the fragment velocity will be low, the following simple approach can be considered, following a method given in [15]:

- a) Calculate the force required to deform the sphere at the point of impact until the yield point of the steel is reached, and the deflection produced. From these the necessary energy (E_y) can be calculated.
- b) Calculate the energy (E_r) required to deform the steel under the point of impact from the yield point through to rupture.

For an impact area with a diameter of five times the vessel wall thickness we find:

$$E_{y} = 7000 J$$
$$E_{r} = 64000 J$$

Allow an equal amount of plastic deformation in the impacting fragment, since it is made of the same type of steel:

Total energy required = $E_y + E_r = 135,000 \text{ J}$

If the fragment weights 20,000 kg (1/10 of a sphere), its velocity = $\sqrt{13.5}$ = 3,7 m/s If the fragment weights 2,000 kg (1/100 of a sphere), its velocity = $\sqrt{135}$ = 11.6 m/s

Using the calculation techniques given in [3], it follows that the actual fragment velocities are much higher (See also Appendix 6). The conclusion is that a fragment from one BLEVE could initiate a BLEVE in a second nearby vessel.

Appendix 8

1º BBZ. op Gitroengeel

Daarna op wit ENKELZ.



APPENDIX 8

PHOTO AND VIDEO MATERIAL

PHOTO AND VIDEO MATERIAL

The available photo and video material contains valuable information for further investigation. The material consists of pictures taken during the disaster (fireballs, people running away from the heat radiation etc.) and pictures taken from the damage after teh disaster.

The locations of the pictures, which are included in this report, could be identified. These spots, together with the spots on the video shots, as well as other photo material are given in figures 1 and 2 in this Appendix.

Additional photo material is available of spots 18, 24, 30, 33, 37 and 41. The video shots are also given in this Appendix.

We like to thank the Mexican Broadcasting company "Televisa" for their kind co-operation and their help to select the most interesting video shots. In this way a videotape of about 33 minutes could be created, which is - and will be in the future - very usefull for the analysis of the incidents.

We further like to express our gratitude to "Ovaciones" for the photos 2, 5, 6, 7, 11, 15, 21 and 22.

GUIDE TO THE VIDEO TAPE OF THE LPG DISASTER AT SAN JUAN IXHUATEPEC (The spot numbers given below, correspond with the numbers given in the figures 1 and 2 of this Appendix)

Counter

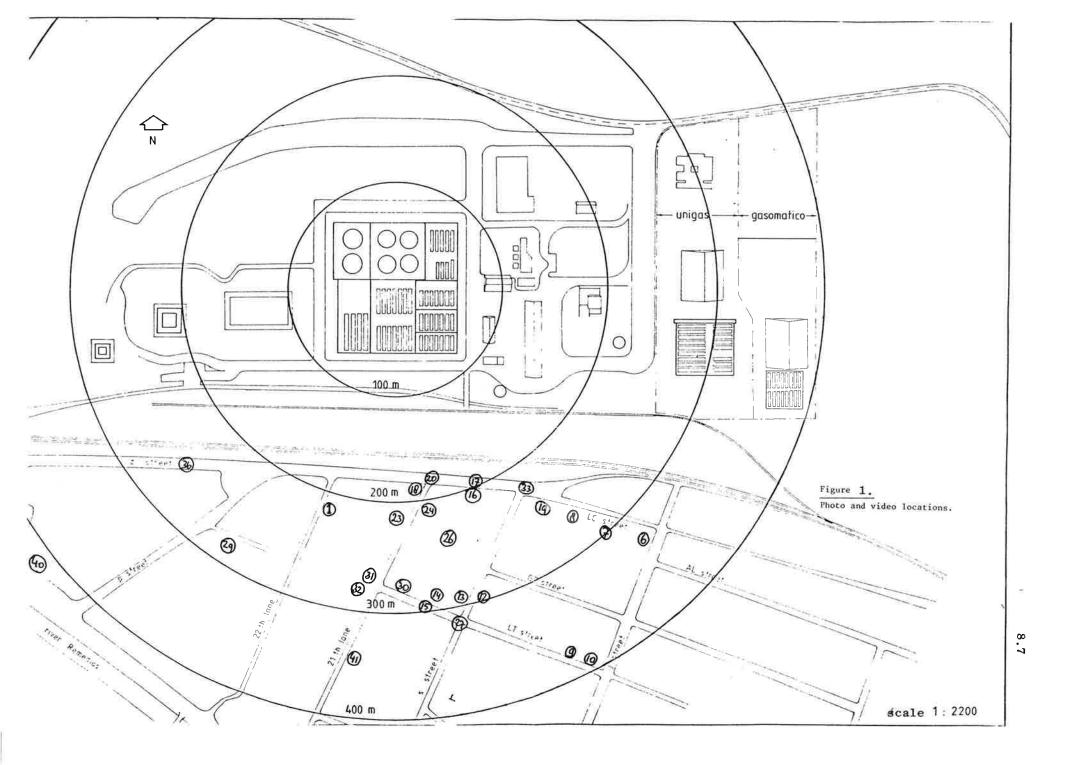
- 0. Houses destroyed at spot 1.
- 6. House at spot 2, 500 m from the plant. Fire in the background.
- 11. Pharmacy at spot 3. Approximately from the same distance as before.
- 12. Entrance to the village through J. Street. Spot 21 (?)
- 14. Fire seen from the south bank of the river. Spot 22, 490 m away from the plant.
- 21. Explosion seen from the previous spot. This explosion occurred at 6.47 a.m., so it probably was the 5th one. According to the camera man the explosion caused a great shock wave that smashed the big windows at the bakery. See counter number scene 122. Even at this distance the heat was so intense that the camera man could not run for cover because of breathing problems. He finally managed to escape through spot 4.
- 34. Another explosion made the camera man drop his camera on the floor.
- 38. Identical to counter number 21.
- 42. Another explosion. There are no data available about the time when this happened. The facts about this particular explosion have been edited and recorded by another crew.
- 50. Windows smashed at 1250 m from the plant. The bridge shown is located 120 m south from where the river Remedios and the motorway cross. Spot 5.

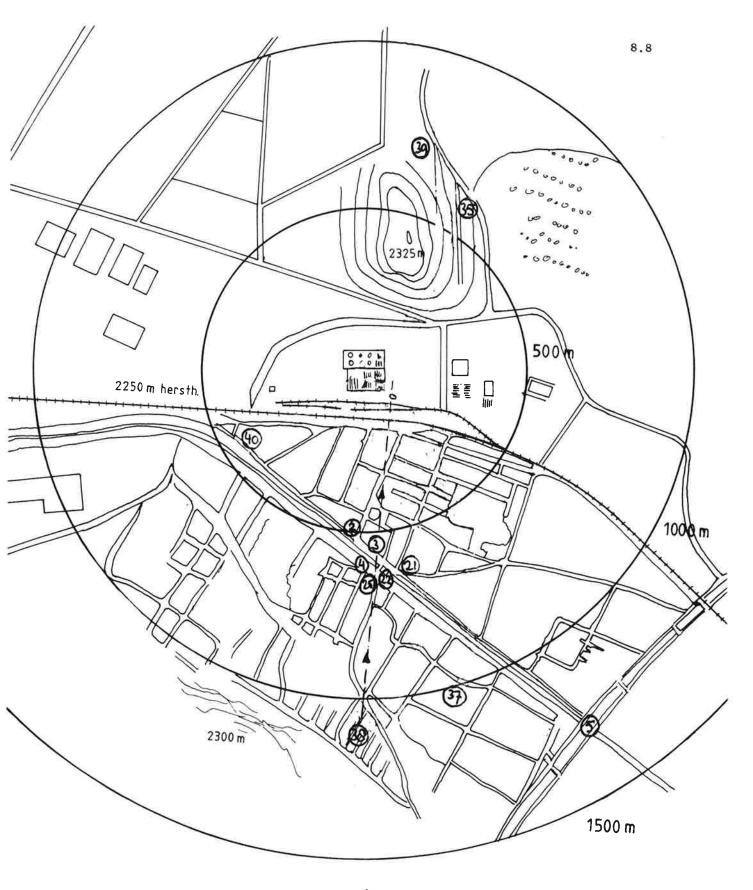
- 51. House destroyed by a sphere fragment at location 6. J.Street near the corner of LC.Street.
- 52. Fire brigade at the crossing of J. and LC.Street.
- 56. LC.Street facing west.
- 57. House destroyed by a sphere fragment at LC.Street. Spot 7, facing south.
- 59. Walk through LC-Street facing west.
- 62. Fire at the plant between 8 and 9 a.m.
- 66. Spot 8 on LC.Street, south-side.
- 68. Fire brigade in action at a house on fire. Spot 7.
- 71. Cushion that used to be on the second floor of a destroyed house. Spot 9.
- 74. Rescue of an injured man. Spot 10.
- 80. LT.Street facing west from the front of spot 10.
- 81. Taken from spot 11. The fire in the background originates from Gasomatico gas trucks.
- 82. House destroyed at spot 6.
- 84. Bus, burned-out at spot 12. A Renault car, burned-out at spot
 13. Both vehicles were parked at S.Street near LT.Street. The view is facing north.
- 86. Burned-out houses at the north-side of LT.Street. Spot 14.
- 88. View of LT.Street facing west. Taken from spot 15.
- 91. Houses on spot 14, still covered in smoke.
- 92. A deceased lying on the road. Spot on LT.Street, facing east.

- 94. Member of the rescue team, trying to break down the door of a house.
- 96. Scene taken at 10 p.m. on the day of the disaster at LC.Street, 150 m away from the plant.
- 99. Spheres on fire.
- 100. Volkswagen car destroyed in front of a house on LC.Street, facing the plant. Spot 16.
- 109. Charred bodies. Spot 16.
- 113. Charred bodies, probably at spot 19.
- 115. Scene taken from spot 20, facing south.
- 115. Stack of bricks at 21th Street. On the left facing south. Spot 24.
- 116. Gas plant.
- 121. Cul de sac at 21th Street. Spot 23.
- 122. Bakery with smashed windows at the south bank of the river. Spot 25, 620 m away from the plant.
- 125. Bridge on the motorway.
- 126. Spheres on fire and view of the plant.
- 132. Fragment of a sphere on the hill facing the plant.
- 133. Unigas and Gasomatico.
- 136. 21th Street towards the plant. Spot 34.
- 137. Unidentified charred bodies. Probably near spot 20, facing the plant.
- 140. Partly charred body.
- 142. Aerial view.

- 160. Ambulances going into the village, early in the morning.
- 162. Stampede around 12 a.m. View from LT.Street towards S.Street. Spot 27.
- 163. Traces of casualties on the ground. Unidentified spot.
- 164. Stampede at the plant.
- 165. Stampede in 21th Street. View from spot 28, looking south.
- 184. Intersection of streets P and Z.
- 166. Spot 18.
- 167. Spot 9.
- 168. Big cylinders on fire at the plant.
- 183. P.Street, Spot 29.
- 187. Burned-out gas trucks. Fragment of a sphere in front of the second truck.
- 188. Plant. Arrow indicates fire underneath the sphere.
- 189. Unigas and Gasomatico.
- 192. Aerial view from the top of J.Street.
- 193. Aerial view from the top of S.Street. The burned-out bus and a twostoreyed house can be seen at the corner of LT. and S.Street.
- 196. Aerial view of a destroyed area at spot 26.
- 197. Dining room and VW, destroyed. Spots 30 and 31.
- 198. Destroyed area at spot 32.
- 200. House destroyed by a sphere fragment at the golf course residential area.
- 201. Uncle S.'s house.

- 202. Charred bodies.
- 204. Spot 18.
- 205. View along 22nd Street from the south. A corpse is lying on the ground on top of a collapsed wall. Spot 1.
- 208. The San Juan church.
- 209. The Basilica de Guadalupe.
- 210. The army.
- 216. Crossing of LC. and S.Street. Spot 33.
- 218. At spot 20, LC.Street becomes Z.Street. View along this road parallel to the railway.
- 219. Deceased. Identical to counter no. 205. Destroyed houses can be seen.
- 222. Area in the neighbourhood of spot 1.
- 225. Identical to counter no. 218.
- 134. View through 21st Street, north of spot 34.
- 227. End.





----→ view from photo ..

Figure 2. Photo and video locations.

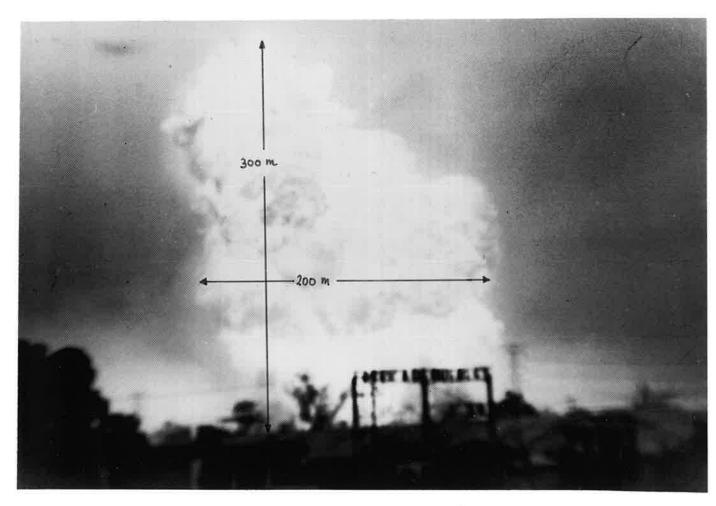


Photo 1 . A BLEVE. (spot 5, at a distance of 1350 m)

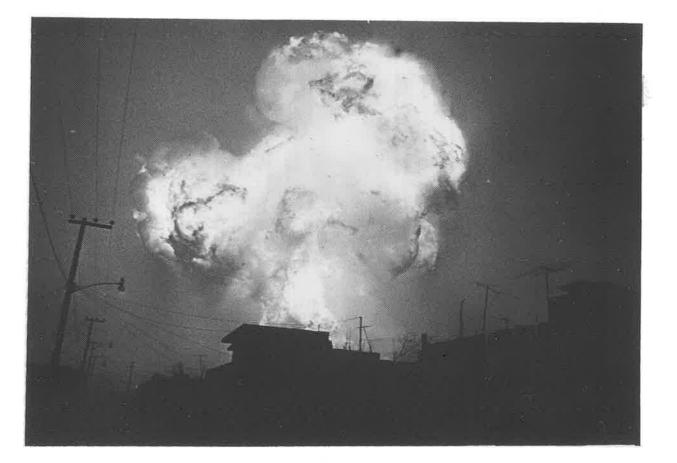




Photo 3. Burning site.



Photo 4 . Fragment close to the spheres

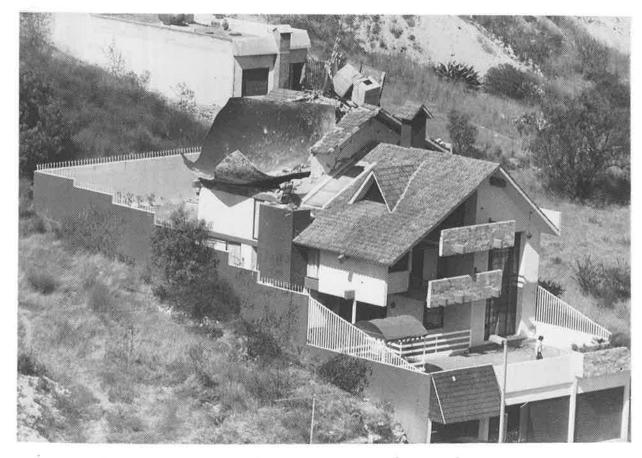


Photo 5. Sphere fragment in El Copal area (spot 35)

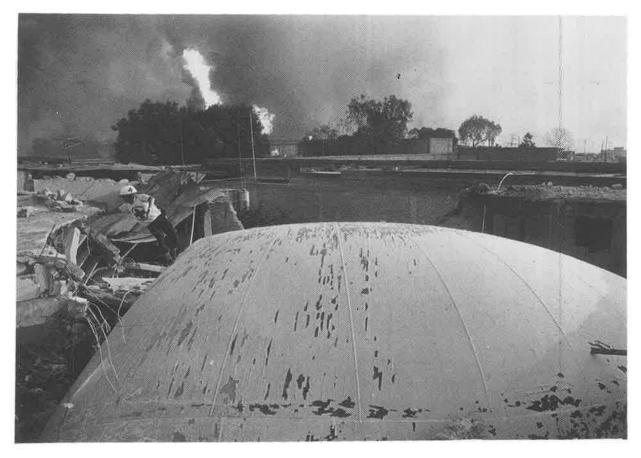


Photo 6. Sphere fragment at spot 40.



Photo 7. Cylindrical "end tub" (spot 10).

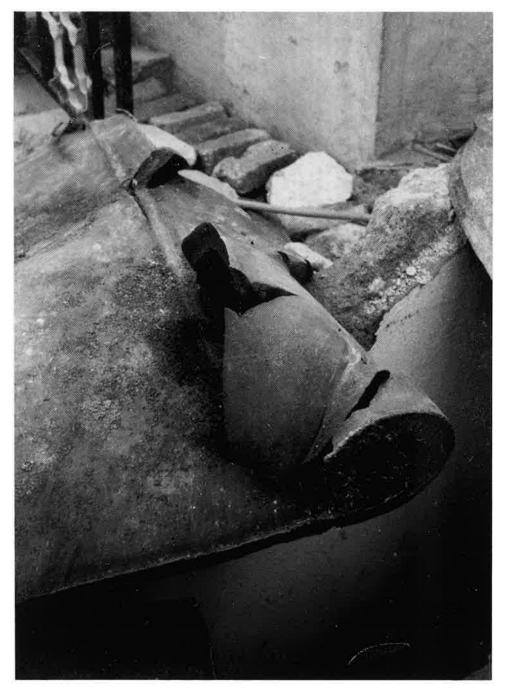


Photo 8. Fragment of cylinder at 1200 m distance.



Photo 9 . Typical fragment of a flattened cylinder.



Photo 10. A major cylinder fragment.

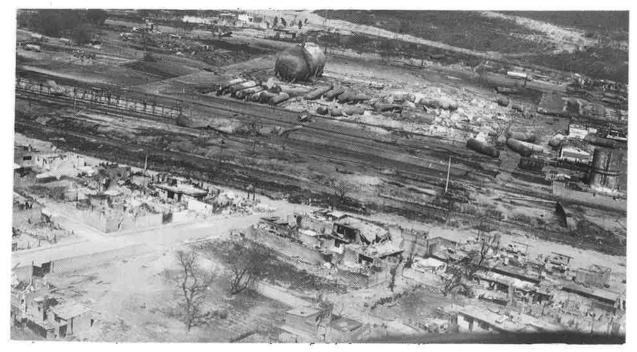
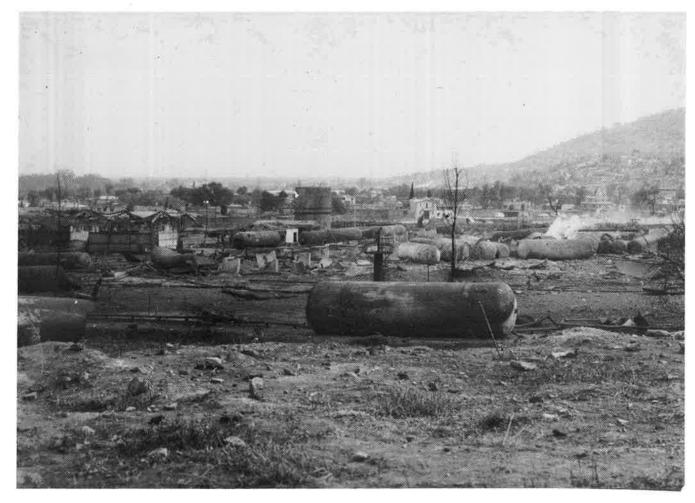


Photo 11. Aerial view, a crossing of 21st Street/Z.Street (spot 20).



Photo 12. Burned out truck at the site.



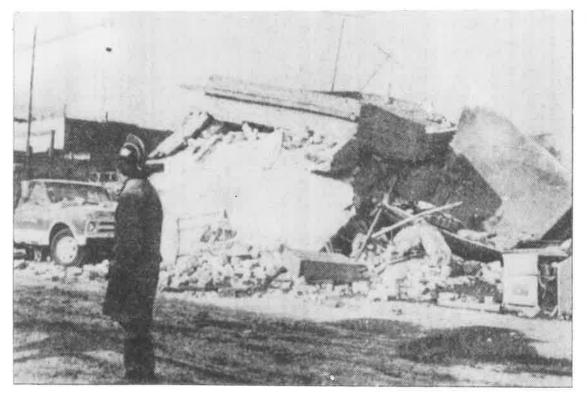


Photo 14. House destroyed by sphere fragment (spot 6).



Photo 15. Destroyed house (spot 1).



Photo 16. Destroyed houses. Unidentified spot.



Photo 17. Destroyed houses, car (spot 13).



Photo 18. Destroyed house at unidentified spot.



Photo 19. Body (spot 1)

Photo 20. 22nd Street (spot 1).



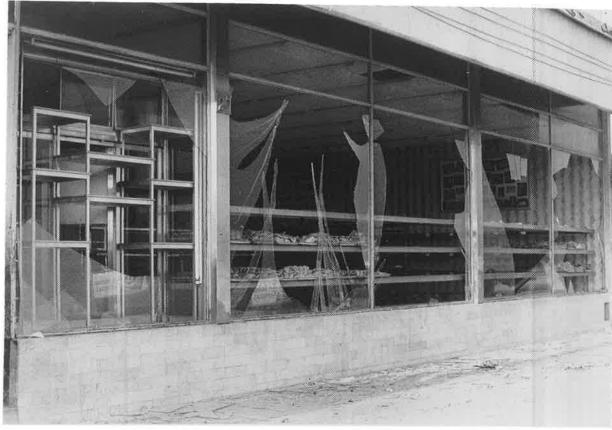


Photo 21. Window damage at spot 25.



Photo 22. Car with paperrolls (spot 36).

8.19



Photo 23. Site in March 1985. Note the new park in destroyed built-up area.



Photo 24. Radiation effect at 1200 m (plastic flags), leaves of trees facing the plant are brown.



Photo 25. View possible from spot 38, taken at about 6.20 a.m.

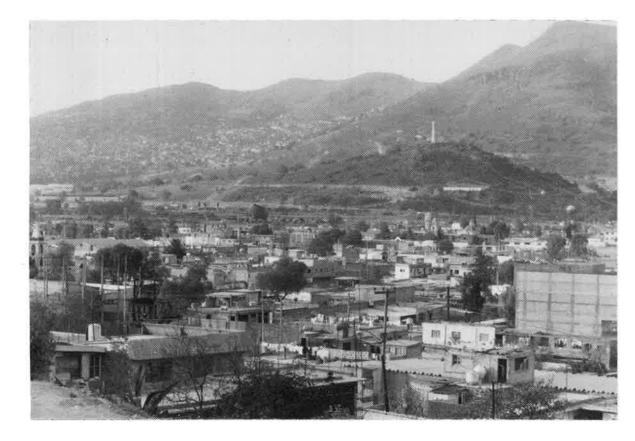


Photo 26. View from same spot as above.



Photo 27. Unigas (r.) and Gasomatico (1.) with destroyed cars with LPG bottles.



Photo 28. Part of the site, March 1985.

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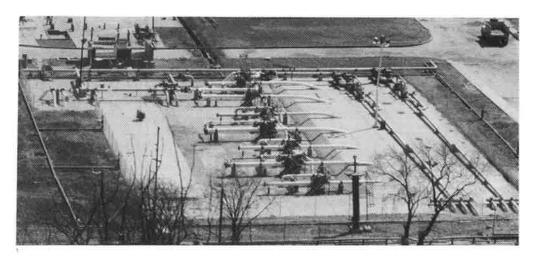


Photo 29. Pipeline manifold.